A HYDRO-ECONOMIC MODEL FOR WATER RESOURCES ASSESSMENTS WITH APPLICATION TO THE APALACHICOLA-CHATTAHOOCHEE-FLINT RIVER BASIN

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A HYDRO-ECONOMIC MODEL FOR WATER RESOURCES ASSESSMENT: WITH APPLICATION TO THE APALACHICOLA-CHATTAHOOCHEE-FLINT RIVER BASIN

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SUMMARY

A detailed hydro-economic model is developed to support multi-objective water resources assessments. The model provides for integrated assessment of physical and economic impacts of changes in water demand, climate conditions, water resources management objectives and policies, and other system constraints on a basin's water resources. A modular modeling approach is adopted in which detailed economic and water resources assessment modules are developed separately and linked through backward and forward exchange of output data. The modeling effort benefits and builds on the extensive work done over the years in the development of the ACF DSS, a comprehensive water resources decision support tool developed by the Georgia Water Resources Institute (GWRI). The model is applied to the Apalachicola - Chattahoochee - Flint (ACF) basin as a case study. However, the methodologies are generic and are applicable to any river basin. The ACF basin is an important source of drinking water for the Atlanta Metropolitan Area, one of the fastest growing metropolitan areas in the US. The basin's water resources also support a vibrant agricultural sector and unique biological diversity.

The study includes two important assessment categories for the ACF basin: (a) Baseline Hydro-economic Assessments that simulate the physical and economic performance of the ACF system under baseline conditions of current water resources management objectives, minimum environmental flow constraints, existing reservoir operation policy, and other system constraints; and (b) Water Resources Policy Assessments that simulate the physical and economic performance of the system under

three potential water management scenarios including (i) implementation of an alternative reservoir operation policy; (ii) relaxation of existing minimum environmental flow constraints; and (iii) water supply restrictions. Baseline assessment results highlight significant changes in physical and economic performance of the ACF system over the period 2000 to 2099 due to increasing pressure on the basin's water resources. The basin is expected to experience reduction in water supply and increase in water demand due to climate and demographic changes. This is attributed to the anticipated reduction in runoff from its watersheds due to projected increase in evapotranspiration associated with higher temperatures in future. Water demand projections indicate significant increase in demand especially in the municipal water supply sector. Implementation of planned investments in efficient water use technologies and improved drainage infrastructure would result in increased return flows there by minimizing aggregate consumptive water use in the basin. Decreased watershed runoff will have a negative impact on reservoir levels and associated non-consumptive water uses that rely on them. Water resources policy assessment results demonstrate the existence and benefits of potential intervention measures that could be implemented to minimize impacts of anticipated water demand growth and potential climate change. The assessments highlight (a) significant economic loss incurred by water users due to water scarcity and inefficient water use; (b) benefits of adaptive water resources management through implementation of more efficient reservoir operation and management policies; and (c) intensifying tradeoffs between upstream and downstream water users.

Overall, the approach provides a holistic analytical framework that generates tangible information for multi-objective water resources decision making and can be used by the relevant stakeholders to reach consensus on potential win-win[1] management and development options.

[1] In a Win-Win scenario, both parties gain more by cooperating than they would otherwise have gained on their own. It's not a matter of all sides reaching an optimal compromise; it's a matter of all sides gaining something.

CHAPTER 1: INTRODUCTION

1.1 Research Background

Many basins in the world are becoming increasingly water scarce due to rapidly growing water demands. Climate variability and change is also exacerbating water stress through increased frequency and severity of droughts and floods. The situation is further complicated by the multitude of water users and stakeholders with conflicting interests. Sustainable use of scarce water resources requires proactive measures that promote water use efficiency and take into consideration the interests of all stakeholders. The measures should be backed by comprehensive assessment and understanding of the economic value of water in different sectors and locations. The assessments should be supported by robust technical tools capable of addressing complex physical and multi-objective management processes in the basins.

Combining engineering, economics, and water resources, hydro-economic tools are well suited to support decision makers and managers address water management challenges in a basin-wide context. The tools provide means to evaluate and guide efficient water use and equitable allocation among competing users. Making the economic impacts of any proposed water policy or management process explicit increases transparency and empowers those who take part in the decision processes. Hydro-economic models are particularly useful in shared-vision planning and integrated assessments by providing useful information to all stakeholders and negotiators involved in the decision making process.

Despite significant advances in hydro-economic modeling and research, several challenges and knowledge gaps still exist. Existing hydro-economic models are limited in their ability to represent some complex physical, economic, and management aspects of a river basin (Griffin, 2006). The most commonly used hydro-economic models are based on economic optimization algorithms subject to some simplified representation of hydrological and water management processes in a given basin. However, in practice, water resources management decisions are complex and multi-objective and ought to be guided by detailed decision support tools capable of representing well the complex physical and management processes in the basin. Furthermore, most hydro-economic studies side-step the issue of uncertainty and error propagation. A few exceptions include Jakeman and Letcher (2003) and Cai (2008) who use sensitivity analysis to reveal parameters or model components with the greatest effect on results. The models are limited in their mathematical representation of water related socio-political and environment management objectives which are sometimes more crucial to water managers and stakeholders than economic objectives.

Few authors have integrated climate change assessments in hydro-economic assessment tools. This is a significant gap given that most water resources managers and policy makers are concerned about potential climate change impacts on future water resources availability and demand. The few studies that have attempted to consider climate change use only a single average future climate change scenario. This approach, though progressive, cannot give useful insights into the wide spectrum of climate change impacts likely to be observed in future. Comprehensive climate change assessments would require consideration of as many climate change scenarios (based on multiple emission scenarios and different Global Circulation Models) as computationally possible and as available data can allow. Besides climate and hydrologic uncertainty, estimates of future water use economic benefits are very sensitive to the variability of economic parameters such as input and output prices/values, and discount rates. These economic parameters are often difficult to project into the future over a long time horizon. Furthermore, projection of future water demands and consumption patterns is a challenge due to difficulty in forecasting future water conservation and demand management practices.

1.2 Research Objective

This research aims is to develop and demonstrate a detailed hydro-economic modeling approach that supports multi-objective water resources assessments. Information generated from the assessments is useful in supporting basin-wide decision making processes aimed at generating consensus on potential win-win management and development options in a river basin context.

The main contribution of this research is the systematic coupling of detailed water resources and economic assessment models that are capable of (a) representing complex physical system characteristics and constraints; (b) simulating system operation at diverse temporal and spatial scales; and (c) representing water-based economic production processes at a basin scale. This research is also unique in that it integrates a wide range of potential climate change impacts on water resources into the hydro-economic modeling framework at a scale uncommon in existing literature. This is achieved through consideration of multiple potential future climate change scenarios based on temperature and precipitation outputs from 13 Global Circulation Models (GCM) under two emission scenarios, i.e., A1B and A2, corresponding to the IPCC's medium and high emission projections. Economic uncertainty is characterized through conjunctive use of Monte Carlo simulation and Geometric Brownian Motion techniques to generate multiple forecast traces of important economic parameters such as commodity prices and input/output costs. Finally, the demonstration of this approach for the ACF River Basin is also novel in that no other detailed basin-wide hydro-economic assessment has ever been carried out for this basin.

1.3 Research Context

Different water resources management contexts require different valuation approaches. For example, estimates of the total water use benefits from a river system, though useful, are a poor guide to water resources policy change and investment decisions. Much more useful in most cases are estimates of the changes in benefits that would result from changes in water management and allocation policies, improvements in water use efficiency, and implementation of water conservation measures. Water value can therefore be looked at in different contexts: its total value or overall contribution to society welfare, the change in this value if a policy change is implemented, and how this change affects different stakeholders—that is, who are the beneficiaries and who are the losers—and how can beneficiaries be made to pay for the services they receive to ensure that the system is conserved and its services are sustained. Each approach has its uses and limitations. Measures of total water use benefits provided by a river system provide useful information on the contribution of water to the overall economy. To assess whether a specific policy change or proposed intervention measure is worth undertaking, we must know two things: what would happen if we did nothing? And what would happen if we did intervene in the proposed way? It is usually the case that change in management policy will increase water use benefits in some sectors and decrease the value of others; what matters is the net difference between the total benefits across all sectors. What is therefore critical to a decision maker and manager is to know whether the total benefits provided by the river system managed in one way is more or less than the total value generated by the system if it were managed in another way. This is basis for the assessments carried out under this research. Estimating changes in water use benefits and costs focuses on only those benefits and costs which are affected by the proposed intervention measure. The scope of the assessment is narrowed to just those benefits that are expected to be affected by the policy change. The key issue is to accurately identify and quantify the changes in outputs of the different sectors that would result from the proposed action.

1.4 Research Approach

A modular modeling approach is adopted in which economic and water resources assessment modules are developed separately and linked through backward and forward exchange of output data. This approach is preferred over the holistic approach to allow for very detailed modeling of the physical system and economic production processes at applicable temporal and spatial scales. It also leverages the strengths of both optimization and simulation solution techniques. On the supply side, detailed hydrological and water resources assessment models are used to simulate the spatial and temporal water availability in different parts of the basin subject to inflow variability, water use withdrawals and returns, and system constraints imposed by different management policies. On the demand side, economic models are used to derive economic benefits accruing from water use in different sectors. The framework supports assessment of relative changes in spatial and temporal water values corresponding to water demand and climate change, changes in water use priorities and management objectives, and variations in system constraints. The methodologies and tools developed are applied to the Apalachicola−Chattahoochee-Flint (ACF) Basin as a case study. However, the methods are applicable to any other basin in the world. A detailed description of the basin including the current state of water resources management and use is given in section 2.7.

1.5 Thesis Organization

The thesis is organized in six chapters beginning with background and introduction to the research and the underlying motivation for it. Chapter 2 reviews relevant literature on hydro-economic modeling principles, water valuation methods, and climate change impact assessments. Detailed description of the research methodology and case study applications is contained in Chapter 3. Chapter 4 presents an overview of methods and results from climate change impact assessments for the ACF basin water resources, recently carried out by GWRI. Chapter 5 discusses baseline hydro-economic assessments for the ACF basin, the results of which provide the basis for bench-marking subsequent water resources policy assessments discussed in Chapter 6. Results are presented for key physical system performance measures including frequency and duration of reservoir depletion, energy generation reductions, water supply deficits, and violation of minimum flow requirements at critical river sections. The economic implications of changes in system physical performance are discussed, as are the vulnerabilities of the ACF system under potential future water demand and climate change. Also discussed are potential intervention measures that could be pursued to minimize the vulnerabilities. Finally, conclusions and recommendations are presented in Chapter 7.

CHAPTER 2: LITERATURE REVIEW

2.1 Economic Valuation

Economic valuation offers a way to compare the diverse benefits and costs associated with water systems, by attempting to measure them and expressing them in a common denominator—typically a monetary unit. Economic valuation can provide useful information for water resources management for example, by highlighting the economic consequences of alternative policy options. Thus economic valuation, used correctly, will lead to more informed choices even when economic considerations are not the primary criterion for decision making.

Economists typically classify ecosystem goods and services according to how they are used. The main framework used is the Total Economic Value (TEV) approach (Pearce and Warford, 1993). The total economic value of water can be broken down into four general categories: (i) direct use value; (ii) indirect use value; (iii) option value; and (iv) non-use value. Direct use values are most often enjoyed by people visiting or residing in the basin itself and include uses such as drinking water supply, irrigation, recreation, hydropower generation, navigation, and others. Indirect use values are derived from water services that provide benefits outside the basin itself. Examples include preservation of environmental health and protection of aquatic ecosystems, which often benefits people far downstream. Option values are derived from preserving the option to use water in the future, services that may not be used at present, either by oneself (option value) or by others/heirs (bequest value). Non-use water values refer to the enjoyment people may experience simply by knowing that the resource exists even if they never expect to use that resource directly themselves. This kind of value is usually known as existence value (or, sometimes, passive use value).

Economic valuation has both strengths and limitations as a tool for decision making. It is clear, however, that decisions about water resources management are not getting easier, and that information about costs and benefits is increasingly becoming essential to ensure efficient, equitable, and sustainable outcomes. Valuation can play an important role in providing such information, provided it is used correctly. Because of data and resource constraints, it is rarely feasible or desirable to estimate every water use benefit or cost. However, even where valuation provides only partial results, it can help to structure how we think about conservation, identify critical information gaps, and clarify the relation between hydrological characteristics of the basin and overall society welfare. Indeed, an important benefit of attempting to undertake economic analysis is that it forces us to grapple with our limited understanding of ecosystem processes and the way they affect human welfare. All too often, public debate and policy on water management and allocation is based on vague statements about the value of water in different competing sectors. Water valuation therefore helps answer important questions like: What specific services does a river system provide? Who receives those services? How important are they? How would each of these services change if the system were managed differently? How big would the change be? What substitutes exist, if any? Simply stating the questions involved in an economic valuation can help to identify what we know and what we don’t know about the role that the river system plays in our welfare.

2.2 Hydro-economic Modeling

The basic philosophy behind integrated hydro-economic modeling is that water systems perform specific economic functions which in turn have direct and indirect impacts on water availability and quality and on the water management processes in the short and long term. Water can be regarded as a direct economic consumption good (e.g., supporting domestic water demand and recreation), or as one of the input factors in crop and food production, energy generation, and other industrial production processes. Water also plays an important role as a buffer for polluting substances that are negative by-products of economic production and consumption processes. Water, therefore, has an economic value by virtue of its use in the different production processes. Hydro-economic models are used to operationalize water resources economic valuation concepts by enabling their integration into traditional water resources management and planning tools. In using these models, water allocations and management are either driven by changes in the economic value of water or economically evaluated to provide policy insights and reveal opportunities for better management. Although including economic criteria adds a layer of theory and complexity beyond traditional water planning models, the wealth of information that hydro-economic models bring to the decision making process justify the additional effort associated with their implementation.

Hydro-economic models are based on detailed representation of the river system linked to relevant economic production activities in the basin through appropriate demand functions. The demand functions depend on exogenous input–output parameters of the economic production process and reflect, at best, a partial economic equilibrium system of demand and supply equations. In the case of agriculture, for example, the demand and supply functions are based on an agronomic model, such as a crop yield function, which depends on factors like soil, crop acreage, rainfall, crop evapotranspiration, and irrigation system characteristics. Economic behavior is usually included through a profit maximization objective function, where fixed and variable production costs are subtracted from the yield benefits subject to the natural resource constraints of land and water availability.

2.2.1 Modular versus Holistic Approach

Existing hydro-economic tools are based on two broad modeling approaches: modular and holistic. The main decision in selecting between these two approaches is whether to solve the economic model endogenously within the water management model, or to estimate water demands with an external economic model and use it as input into the water management model. The modular approach provides for a loose connection between the hydrologic and economic components with output data from one module usually providing the necessary input for the other module. In principle, the modules operate independently of each other and systems of equations are solved in an exogenous way. The various sub-models can be very complex and the main challenge is to find the right transformation of data and information between sub-models. In the holistic approach, there is one single unit with both the hydrologic and economic components closely linked in a consistent modeling framework and all the relevant variables solved endogenously (Cai and Wang, 2006). The main strength of the modular approach is its ability to go into more detail in each sub-field, and the ability to be independently updated and developed. On the other hand, holistic models can more effectively represent causal relationships and interdependencies between the physical and economic processes in the basin. In addition, scenario-based studies such as climate change impact studies are easier to execute with holistic models since they do not require representing the changed policies or conditions separately for each submodel. The main weakness of the holistic approach is that solution of the complex system of simultaneous equations requires that the different physical, economic, and management processes in the basin be represented in a simplified way (McKinney et al., 1999). Draper et al. (2003) and Howitt et al. (2001) apply the modular approach by using exogenous economic models to determine water use scarcity cost curves. A holistic approach is presented by Cai et al. (2003a) where water demand curves are estimated endogenously.

2.2.2 General Equilibrium Modeling

Unlike holistic and modular modeling approach, Computational General Equilibrium (CGE) modeling approach focuses on the overall regional economy and assesses the impact of water policy changes on the outputs of all sectors of the economy. CGE models are a standard tool of empirical analysis, and are widely used to analyze the aggregate welfare and distributional impacts of policies whose effects may be transmitted through multiple markets, or contain menus of different tax, subsidy, quota or transfer instruments. Examples of their use may be found in areas as diverse as fiscal reform and development planning (e.g., Perry et al 2001), international trade (e.g., Harrison et al 1997), and increasingly, environmental regulation (e.g., Weyant 1999; Goulder 2002). CGEs start the integration process from the economic system and attempt to link economic relationships to the hydrological system.

Regional economies are characterized by diverse production sectors that are closely interdependent as output from one sector forms input to other sectors and vice versa. As a result, when consumers purchase goods from a particular business, industries that supply goods or services to that business are also affected. The goal of input/output modeling is, therefore, to capture and quantify these interdependencies within the general economy. However, characterizing the complex linkages and interdependencies of a regional economy is a time intensive exercise that requires large amounts of detailed data covering all production sectors of the economy. The data is assembled in a very detailed input/output matrix, which enables tracking of flows of goods and services within the entire economy. The matrix demonstrates how each sector's input needs are met by the outputs of all other sectors within a specified geographic area. Manipulation of the input/output matrix generates a set of values known as multipliers, which further characterize the regional economy. Multipliers quantify the relationship between the demand for a given sector's output and the corresponding output required of the regional economy. Increased demand and spending in a given sector ripples through all production activities linked to that sector. Multipliers capture the effects of changes in demand/ expenditure in a given sector on the economy. The magnitude of the multiplier is proportional to the cumulative impacts the sector has over the general economy.

An important aspect of regional economic modeling is the definition of the study area. This entails clear demarcation of the actual site of the impact, the location of secondary industries, the residential location of the labor force and the appropriate pathways through which the goods and services flow in the entire economy. Detailed economic data of this nature, however, are rarely available at a local scale. Most regional economic analysis, therefore, rely on state or federal level data to approximate local economic impacts. This approach, though progressive, could result in erroneous results especially in situations where the configuration of the economy geographical area under consideration is quite different from that of the state or federal level.

A number of regional economic models exist in literature. The IMPLAN (Impact Analysis for Planning) is one of the most commonly used regional economic models in the US. The model was originally developed by the U.S. Forest Service and is currently used by many state and federal planning agencies to evaluate economic impacts of diverse policy choices. The IMPLAN input/output matrix incorporates data from a number of federal and state entities, including the Bureau of Economic Analysis and the Bureau of Labor Statistics. The IMPLAN model allows the user to examine how increase (or decrease) in expenditures in one sector would ripple through the regional economy. The model estimates the total change in key economic factors such as output, income, and employment corresponding to a given change in output in a specific sector of the economy.

Several examples of CGE applications in water policy assessments exist in literature. Brouwer et al. apply a disaggregation procedure for the macroeconomic effects of water policy scenarios estimated with the help of a CGE model to different river basins based on an integrated national and river basin accounting system. In their study, Strzepek et.al apply a comparative static CGE to evaluate the economy-wide impacts of the High Aswan Dam on the Egyptian economy. Van Heerden et.al apply a comparative-static CGE approach to model water demand in two of the most water intensive sectors in the South African economy (irrigated crop production and forestry).Water is included in the model through sector specific water demand functions and the introduction of a water use tax. Despite their appeal in enabling modeling of economy-wide impacts, CGEs are criticized for being too general and for not being able to represent more detailed hydrological and other physical processes in a river basin.

2.3 Economic Valuation of Irrigation Water Use

Two general approaches are used for valuation of irrigation water use: inductive and deductive valuation methods (Young, 2005). For the inductive approach, water is considered to be a variable input, whereas in the deductive approach water is hypothesized to be a limiting factor. Inductive methods are based on statistical analysis of observed crop production data whereas deductive methods use optimization techniques to model the behavior of a profit-maximizing farmer.

2.3.1 Inductive Valuation Methods

Inductive techniques are empirical water valuation methods often based on observed water market transactions, econometric estimates or hedonic property valuation. They involve use of statistical methods (e.g., regression analysis) to derive an appropriate production function from empirical data. The irrigation water demand curve is derived from the product of the marginal physical product and the respective crop prices for different quantities of irrigation water use. The main advantage of inductive methods is that they are based on observed crop production data and farmer behavior. However their main weakness is that they are data intensive and tend to be unreliable when used to evaluate hypothetical policies and scenarios not reflective of historical data and farmer behavior (Young, 2005). Young (2005) provides several examples of valuation studies that use inductive techniques to estimate water value for both disaggregated and aggregated data.

2.3.2 Deductive Valuation Methods

Deductive techniques are the most commonly used valuation methods for estimation of irrigation water value. Models of farmer behavior are calibrated and used to estimate willingness to pay for irrigation water as a difference between forecast crop revenues and anticipated costs of purchased inputs other than water, and opportunity costs of owned inputs. Different versions of these models are used in practice ranging from simple farm crop cost and return budget of net return for a single crop to more complex multi-crop optimization models that represent optimal allocation of irrigation water and other production inputs among several potential crops. Mathematical programming falls within this category and is perhaps the most widely used method. Using the deductive technique, the model is solved for each of a number of increments of water supply and the net return to each increment of water derived from the incremental change in the objective function (Bernardo et al., 1987). The objective function value for each solution of the model provides an estimate of the value of water for the supply scenario assumed for that solution. The marginal benefit function can then be determined. The main advantage of deductive techniques is their flexibility and ability to analyze hypothesized future policy options based on alternative assumptions about changes in input and output prices, irrigation technology, and crop mix, among other factors. Deductive methods, with their explicit constraint structure and basis in optimization, can readily incorporate new policies as additional constraints. The main criticism is their over estimation of irrigation water value due to the inability to account for opportunity costs of all production inputs (especially opportunity costs of owned inputs such as labor and capital resources; Scheierling et al., 2006). Secondly, forecasts of future crop prices and yields tend to be over optimistic resulting in inaccurate revenue projections. Other common concerns include over simplification of farmer decision-making processes and failure by most analysts to adjust input prices for farm subsidy programs where applicable (Young, 2005).

Several production function forms have been used in applying the deductive valuation approach in past studies. Examples include the Constant Elasticity of Substitution (CES) production function (Medellin-Azuara, 2006; Medellin-Azuara et al., 2009), Cobb-Douglas production function (Young, 2005), and Leontieff production function (Florencio-Cruz et al., 2002; Tsur et al., 2004). The CES production function (Arrow et al., 1961) exhibits constant elasticity of substitution σ between input factors, which allows them to either be complements or substitutes depending upon the value of σ (sigma). The Cobb-Douglas, Leontief, and Linear production functions are special cases of the CES production function. That is, CES yields the Cobb-Douglas function as σ approaches 1, the linear (perfect substitutes) function as σ approaches positive infinity, and the Leontief (perfect complements) function as σ approaches 0.. The correct choice of sigma is a purely empirical question. The restriction in the value of sigma implies that factor shares will remain constant despite changes in factor inputs because any changes in factor proportions will be exactly offset by changes in the marginal productivities of the factor inputs. This formulation of the CES function has been criticized as being unduly restrictive because it limits the extent to which one input can substitute another and assumes that technological progress has no effect on the marginal productivities of input factors. The translog production function (Christensen et al. (1973)) is even more general, as it does not require that the elasticity of substitution be constant across factor inputs.

Extensive literature exists on the application of inductive and deductive techniques in the economic valuation of water in irrigated crop production. Scheierling et al. (2006) carried out an extensive Meta analysis of irrigation water valuation literature and observed price-elasticity for irrigation water to be predominantly inelastic averaging about -0.48 with a median of -0.16. The study also found the elasticity estimates to be sensitive to the valuation technique used. Estimates using mathematical programming or econometric methods were often higher than those obtained from field experiments. Young (2005) reviews several studies that have used a Cobb-Douglas production function to estimate water value for both disaggregated and aggregated data. Moore et al. (1994) offered a multi-crop production model using micro-farm data. Howitt, Watson, and Adams (1980) use quadratic programming methods to model irrigation decisions by allowing crop prices to vary with regional output of irrigated crops. Berck, Robinson, and Goldman (1991) use a computable general equilibrium model of agricultural water use in southern San Joaquin Valley. Howitt (1995) combines regional equilibrium models and positive mathematical programming (PMP) to calibrate flexible crop production functions. Optimization models of inter-sectoral regional water allocation by Vaux and Howitt (1982) and Booker and Young (1994) incorporate demand functions for water to solve for optimal prices of water in a regional or basin-wide context. Taylor and Young (1995) developed a discrete stochastic sequential programming (DSSP) model of sequential uncertain multi-crop production process characteristic of irrigated agriculture. They show that benefits increase with increasing reliability of water supplies. Knapp and Wichelns (2001) review the dynamic optimization approach with extensions to water quality and drainage. The dynamic programming approach provides a rigorous representation of the problem of sequential water-use decisions in the face of uncertain water supplies. A recent review of applications of deductive techniques in water valuation studies can be found in Johansson (2005).

2.4 Economic Valuation of Municipal Water Use

Economic valuation of municipal water use is usually based on the economic concept of willingness to pay (WTP). Several approaches exist in literature for estimation of WTP for municipal water supply. Where the market price of water is representative of its marginal cost, the observed market price can be used as the basis for estimating the willingness to pay for incremental water supply. However, in practice, such situations are very rare. If there are no observed market prices or if the market prices do not reflect the marginal costs of water production, other indirect methods can be used to estimate willingness to pay for incremental water supply. A brief description of some of the commonly used methods for valuation of municipal water use is given below.

2.4.1 Contingent Valuation Method

Contingent Valuation Methods (CVM) use surveys to ask consumers directly what they would be willing to pay contingent on some hypothetical change in municipal water supply. This method is particularly useful in situations where the WTP cannot be inferred directly or indirectly from market observations. The main attraction of this method is that it can be used to evaluate potential scenarios (e.g., water shortages due to droughts) before they actually occur or proposed policy changes (e.g., demand management/water conservation measures) prior to their implementation. Thomas and Syme (1988) applied CVM to value residential water use in Perth, Australia. Carson and Mitchell (1987) surveyed California residents about their willingness to vote for a hypothetical initiative that would increase water supply reliability at a given cost. Results of this pioneering study support estimates of median annual willingness to pay (WTP) per household to avoid specified water shortages. McClelland et al. (1994) applied the CVM on a study of willingness to pay for household water and sanitation services in Lugazi, Uganda. Consumers were allowed to choose a level of service and informed of the cost. The survey revealed that most consumers were willing to pay significantly high prices for a modest change in water supply level (from unreliable vendors to public taps, considered to be more reliable). The main weakness of the CVM is that not all respondents have the same understanding and interpretation of the questions when responding to the survey.

2.4.2 Econometric Methods

Econometric analysis is the most commonly used approach to modeling municipal water user behavior (Kindler and Russell, 1984). The approach makes inferences from actual observations on quantities of water consumed, together with the corresponding data on water prices, incomes, climatic variables, and other relevant factors. An abstract demand function is derived, using multiple regression analysis, describing the relationship between water consumption and the other parameters. The water demand function is usually represented graphically by the demand curve, or algebraically as: $Q_w = Q_w (P_r, P_a, P; Y; Z)$; Where Q_w refers to the individual's level of water use in a specified time period; P_r refers to the price of water; P_a denotes the price of an alternative water source; P refers to an average price index representing all other goods and services; Y is the consumer income, and Z is a vector representing other factors, such as climate and consumer preferences.

Renzetti (2002) and Schneider and Whitlach (1991) present comprehensive summaries of some of the most detailed water demand studies carried out in the past, and also provide an extensive survey of the existing literature on the subject. The latter analyzed a very large data set (some thirty years of individual accounts from a number of communities supplied by the City of Columbus, Ohio, water system) and derived short run and long run demand functions for each of five sectors (residential, commercial, industrial, government, and schools) as well as for the total of all metered demand accounts. Griffin and Chang (1991) confirmed from a sample of Texas counties that demand differs between winter and summer. Their study showed demand is somewhat more inelastic in winter (about -0.3) than in summer (about -0.4). Lyman (1992) compared peak with off-peak demands from a small Idaho city, finding a quite elastic response to peak prices, while long-run off-peak price elasticity was inelastic with respect to price. Hewitt and Hanemann (1995) reassessed a data set representing individual household observations, finding seasonal demand elasticities much greater than had previously been reported. Renwick and Green (2000) analyzed cross-section monthly time-series data for eight large water agencies in California for the period 1989-1996 to isolate the effects of non-price conservation policies and water price. Their study concluded that residential water use is affected by both water price and non-price water demand conservation practices. Espey et al. (1997) carried out a meta-analysis of several past studies in the United States and observed that the estimated price elasticities ranged from -0.02 to -3.33 with a mean of -0.51. Following another extensive review that accounts for the average cost bias and excludes commercial users, Young (2005) suggests

-0.3 to -0.6 as a plausible range of price elasticity of demand for residential water use in the United States, signifying an inelastic demand that is generally price responsive.

2.4.3 Observed Demand Functions

In practice, consumers are willing to pay considerably more than what utility companies charge them for municipal water supply, particularly if the alternative is water shortage. The difference between what they are willing to pay and what they are actually charged is referred to as consumer surplus. The charge for the water plus the consumer surplus is the total value of the water to the consumer, also referred to as the total benefit value of municipal water supply. If a demand curve for municipal water supply exists, it can be used to estimate the willingness to pay for each additional unit of municipal water supply. The total WTP for a specific additional quantity of water is estimated as the area under the demand curve between the original and final water supply quantities.

Other methods that have been used by some authors include hedonic price method (North and Griffin, 1993), and other engineering technical approaches (Howe, 1971).

2.5 Economic Valuation of Recreation Water Use

Because recreation is largely a public good, it is usually not possible to estimate demand directly from price-consumption data. As a result, empirical approaches, including travel cost methods, contingent valuation surveys, or proxy values such as unit day visitation values are often used to infer recreation water values.

2.5.1 Travel Cost Method

The travel cost method is the most commonly used technique for valuation of recreational water use. Its main advantage is that, like other revealed preference methods, the method reflects actual consumer choice behavior, which is preferable to methods which rely on responses to questions regarding hypothetical scenarios (Young, 2005). The underlying assumption behind the use of this method is that consumers respond to higher travel costs in the same way that they would respond to higher entrance fees to a recreational site. A demand schedule for recreation at the site can, therefore, be derived from the costs of travel (Freeman, 1993). The costs of travel themselves are not a measure of the recreational water use value but are used to infer the desired consumer surplus as an integral of the area below the demand curve and above the applicable cost of travel. The travel cost approach involves two steps: the first is to estimate the individual recreationist demand for the resource, and the second is to statistically derive the relevant aggregate resource demand curve. The main concern in using the travel cost method is that water is likely to be only one of many attractive attributes of a recreational site, and people travel to rivers or lakes for a multiplicity of reasons, some of which may be unrelated to water supply or quality. To obtain the value of the water or of a water quality improvement, some method must be devised to isolate the contribution of water to the total estimated site value. One approach to address this challenge is to perform a multiple site analysis. For example, Smith and Desvouges (1986) developed a generalized travel cost model designed to infer the value placed on water quality improvements by recreationists for a sample of U.S. Army Corps of Engineers reservoirs. Another challenge is that, as with any economic good, the availability and cost of substitutes are significant determinants of demands for recreational sites. If relevant substitute recreational activities are not accounted for in the analysis, the estimates of consumer surplus will be biased (Burt and Brewer, 1971).

Few studies exist on assessing the value of water level fluctuations on water based recreation. Connley et al. 2007 developed stage-damage curves and used them to estimate net economic value of recreational boating as a function of water level fluctuations in Lake Ontario and the St. Lawrence River. Their study used data gathered from a survey of recreational boaters to determine days boated and willingness-to-pay for boating on the two water bodies. Cordell and Bergstrom (1993) studied the impact of alternative reservoir water level management scenarios on recreational use values for four western North Carolina reservoirs. The study concluded that users placed the highest value on keeping water levels high through the summer and fall seasons. However, the study did not link their results with usability of the reservoir for recreation at specific water levels. Allen et al. (1996) evaluated the effects of potential water management alternatives on water-based recreation use at 25 water resource projects, rivers, and river reaches in the ACT and ACF river basins. The study used estimated boater expenditures to infer the impact of water level fluctuations on the net recreational benefits. Hanson and Hatch (1998) used the contingency valuation method to estimate recreational use value and assess the impact of hypothetical changes to reservoir water management policies for Lake Martin in Alabama. The study also developed regression functions that were used to estimate recreational value changes corresponding to changes in summer full-pool water level resulting from alternative water allocation decisions. In a study for the Atlanta Regional Commission (ARC, 2004), surveys of actual expenditures by local and out-of-town recreation visitors to Lake Lanier were used to estimate recreation water use benefits for the lake. The study observed that recreation benefits were sensitive to lake level fluctuations, which were affected by existing reservoir release rules and priorities.

The study also showed that municipal and industrial water supply, recreation, and water quality were the most valuable water uses of Lake Lanier compared to hydropower generation and navigation. Based on the 2004 visitation rates and expenditures, the study estimated the local recreation benefits for Lake Lanier to be 278 million dollars.

2.6 Economic Valuation of Water Use in Energy Generation

During energy generation, water is either used directly to run turbines during hydropower generation or indirectly as cooling water requirements in thermal power generation. Valuation of water use in these two cases is discussed below.

2.6.1 Hydropower Generation

Though market data on hydropower sales may be readily available, it cannot be used to directly infer the economic value of water in hydropower generation. An appropriate measure of economic value is the cost avoided by utilities in substituting hydropower for the best available alternative (Munasinghe and Warford, 1982). The alternative cost technique is the preferred approach because most firm energy sales are fixed by long term contracts whose prices are heavily regulated by government agencies. The observed market prices seldom reflect the true marginal cost of hydropower supply. Secondly, electricity is sold into a power grid relying on a number of sources (including hydro, thermal, and nuclear), and it is not possible to specifically derive the demand for the hydro portion of the region's electrical supply. Depending on the objective of the study, short or long run water values may be computed. Short run values are derived by deducting only operation, maintenance, and repair costs from the total output value, and are suitable for short run reallocation decisions. Long run values are developed for long run investment and reallocation decisions, by further deducting capital investment costs.

This opportunity cost is measured in the short run by the operation and maintenance costs of alternative electrical generation capacity, minus the operation and maintenance costs of hydropower generation. An additional premium is added if significant differences in transmission costs are incurred. If excess capacity does not exist in the future, then capital costs of constructing additional generation capacity are also added. Another difference in water values can be attributed to the price difference between peak and off-peak power. Thus, water used for peak power generation is more valuable than in base load generation.

2.6.2 Thermal Energy Generation

Development of economic demand functions for cooling water is based on the cost of alternative cooling technologies. The most commonly used cooling technologies include once-through cooling systems, cooling ponds, wet tower cooling, dry tower cooling, and hybrid wet/dry cooling towers. Despite the large amounts of water diverted, once-through cooling technologies are still used in several thermal generation plants in the ACF basin. These systems are also associated with water temperature increases of the receiving water bodies. The wet cooling towers have been adopted in several thermal power generation plants as replacement for the once-through cooling systems. Though they require less water diversions, evaporation from the cooling towers can be significant. Dry cooling and hybrid wet/dry cooling systems are slowly being introduced to replace cooling towers and reduce evaporative losses. However, these systems are very expensive relative to the total power generation costs, thus hindering their wide spread adoption.

2.7 Characterization of Economic Uncertainty

Estimates of economic benefits over a long time horizon are very sensitive to variable economic parameters such as input and output prices/values, discount rates, and elasticity that are difficult to project into the future. Due to short term supply and demand imbalances, short-term prices (spot prices) tend to exhibit significantly different behavior than long-term prices (forward prices). A point forecast based purely on the most likely, or expected, prices therefore gives only the most probable outcome for each assessment period. Such a forecast represents one sample path out of myriad potential sample paths. In forecasting commodity prices, care is taken to ensure that the stochastic processes used capture the specific characteristics of the commodity. For example, energy prices typically display seasonal variations in volatility, occasional price spikes, and a tendency to quickly revert to the average cost of production.

Monte Carlo simulation applies a selected model (a model that specifies the behavior of the economic or physical process of interest) to a large set of random trials in an attempt to produce a plausible set of possible future outcomes. When a structural model generates a large number of Monte Carlo simulations of the system, it captures physical or instantaneous volatility as well as the temporal variation in price levels. The simulation results are used to generate a distribution of hypothetical future outcomes. The Geometric Brownian Motion (GBM) technique is one of the most commonly used method to simulate commodity prices. A GBM is a process in which the change in a variable (for example, price) is related to a growth trend through time and a variation around the trend. GBM uses a known stochastic process to describe future values of a variable based on a combination of current values and a random variable. The underlying assumption in GBM price forecast is that price follows a series of steps, where each step is a drift plus or minus a random shock. While the period returns are normally distributed, the consequent multi-period price levels are log normally distributed. The stochastic element is based upon the standard normal distribution and the square of the change in this part of the process is linearly related to the time dimension.

If the price evolution of a given commodity follows a GBM, the change in the net price is given by the differential:

$dP = P(\mu dt + \sigma dz)$

where:

μ : the growth rate (expected return),

t : time,

σ : the standard deviation of returns,

$dz = \varepsilon(dt)^{1/2}$, with dz being normally distributed and independent of historical price fluctuations,

ε : a standard normal variable.

In this equation, μ is the drift term that gives direction to the movement of the instantaneous rate of return, while σ is the volatility term, which describes its tendency to undergo price changes.

In order to simulate possible future prices following GBM, one only needs the current commodity price and its expected variability (volatility). Therefore, the only unknown parameter in the GBM is the volatility of the future commodity prices. The ideal volatility to use for modeling purposes would be the "future volatility", but by definition, it is not possible to know "future volatility" until one knows what has happened in the market. Therefore, the volatility curve used as an input should be our "best estimate" of future volatility, and reflect our expectations regarding the variability of the commodity price over the period of time under consideration. There are several methods used to estimate "expected" volatility. Some authors prefer to use estimates based on historical prices ("historical volatilities"), while others use the volatilities implied by option market prices ("implied volatilities"). This research uses the historical volatilities approach. Using historical price sequences, compute the continuous returns as the natural logs of the relative prices [$Ln(P_{t+1} / P_t)$]. Compute the volatility (σ) as the standard deviation of the returns. Under GBM, volatilities are proportional to the square root of time. The process of converting volatilities between different time horizons is known as the square-root-of-time rule. This rule allows us to annualize hourly, daily, weekly, monthly or any other volatilities.

The main criticism of the GBM technique is that it assumes constant price volatility. In practice volatilities are known to change over time, and the assumption of constant volatilities may, therefore, not be very realistic. For example, energy prices and volatilities are known to be characterized by strong seasonal variability that should be taken into account in the forecasting process. The standard deviation of energy prices is greatest in the months of July and August, which also experience the highest monthly energy demand. In this case the constant volatility parameter (σ) is replaced by a time dependent one ($\sigma(t)$). The other weakness of the GBM technique is that when volatility is significantly large, the drift component starts to dominate the price evolution. Therefore, for commodity prices with very high volatilities and mean reversion (e.g., power), it is highly recommended to use more complex forecasting techniques that better describe the evolution of the underlying price process (e.g., mean reversion or jump diffusion techniques). The mean reversion model and jump diffusion model aim to modify the general diffusion price process in order to capture these additional market realities. Despite its weaknesses, GBM is still the most commonly used commodity price forecasting technique, largely due to the relative simplicity of estimating input parameters.

2.8 Climate Change Assessment

Despite the existence of an extensive body of research about climate change and its potential impacts on water resources, decision makers and managers are still concerned about the ability of existing water management plans and water supply infrastructure to cope with these impacts and what the economic cost of inaction could be. Unfortunately, precise quantitative information on potential impacts of future climate change is unavailable. While findings from most climate change studies show good consistency in projections of future temperature, considerable inconsistencies exist in precipitation estimates due to significant differences among existing GCM predictions. As a result, considerable uncertainties about precise impacts of climate change on hydrology and water resources will remain until more precise and consistent information becomes available about how precipitation patterns, timing, and intensity will potentially change in future. Consequently, water managers must explore the sensitivity of their plans and infrastructure to a wider range of potential future conditions, and develop methods or technologies to improve their performance.

Projecting regional impacts of climatic change and variability relies first on General Circulation Models (GCMs), which develop large-scale scenarios of changing climate parameters, usually comparing scenarios with different concentrations of greenhouse gases in the atmosphere. This information is typically at too coarse a scale to make accurate regional assessments. As a result, more effort has recently been devoted to reducing the scale and increasing the resolution of climate models through various techniques such as downscaling or integrating regional models into the global models. The extent and severity of climate change impacts varies with location and sector. In a recent study on the impact of climate change on the water resources of the ACF basin (Georgakakos et al., 2010, and Zhang and Georgakakos, 2011), the authors observe that while on average precipitation in the basin is not expected to change relative to the historical baseline, its distribution is expected to “stretch” becoming wetter and drier than that of the historical climate. The study concludes that the coming decades are likely to usher in more severe floods and droughts than those experienced in the basin over the historical past. Decision makers and managers are concerned about the potential risks of floods and droughts posed by future climate change. Hydrological fluctuations due to climate change impose two types of costs on society: the costs of building and managing infrastructure to provide more even and reliable flows, and the economic and social costs of floods and droughts that occur in spite of these investments. Future flood damages will depend on many factors including level of investment in flood protection measures, extent of development in floodplains, and the nature of climate-induced changes in hydrological conditions, sea levels, and storm surges (USEPA 1989). At the other extreme, prolonged drought affects virtually all sectors of the economy. The agricultural sector is particularly vulnerable to climate change to the extent that even relatively small changes in water availability could lead to relatively large impacts in agricultural production (Brumbelow and Georgakakos, 2000). Specifically for the energy sector, significant investment in alternative sources of energy, combined with energy conservation, would be required to cope with the decreased hydropower production due to climate change. Several regional climate change studies indicate that large changes in the reliability of water yields from reservoirs could result from even small changes in inflows due to climate change (Nemec and Schaake 1982; USEPA 1989; Lettenmaier et al. 1999; McMahon et al. 1989; Cole et al. 1991; Mimikou 1991a,b; Mimikou and Kouvopoulos 1991; Nash and Gleick 1991a, b, 1993).

2.9 Review of past studies

Recent hydro-economic modeling research has been described by, among others, Rosegrant et al. (2000), Lund et al. (2006), Cai et al. (2003), Ward et al. (2009), McKinney et al. (1999), Jakeman and Letcher (2003), Heinz et al.(2007), and Cai (2008). Harou et al (2009) gives a comprehensive review of over 80 past hydro-economic modeling research efforts. Draper et al (2003) developed a hydro-economic model called the California Value Integrated Network Model (CALVIN) whose overall objective is to minimize total water scarcity and operation costs in California's interconnected water system. The modeled water system comprises of 51 reservoirs, 28 groundwater basins, and 54 economically represented urban and agricultural demand areas, along with over 1,250 links representing the State's natural and built conveyance system. As a deterministic optimization model, CALVIN's main inherent weakness is the assumption of perfect hydrological foresight (Howitt, 1999). The model minimizes total water scarcity and operation costs based on perfect knowledge of the hydrology for the entire modeling period. In addition, the model does not address hydrological and economic uncertainty which could have significant ramifications for sustainable water resources management and water use. In some of the recent studies, Jeuland (2010) developed a hydro-economic modeling framework for integrating climate change impacts into the problem of planning water resources infrastructure developments. However, the study only uses a single climate change scenario (constructed based on the IPCC ensemble mean projections for A2 emissions scenario) for comparison with historical conditions and thus fails to give insights into the potential range of climate change impacts. In a study conducted for the California Energy Commission, Kiparsky et al. (2005) carried out an extensive literature review on climate change and its impacts on the water resources of California including the economic implications of climate change mitigation and adaptation. The study highlights the challenge of characterizing physical and economic uncertainty associated with potential climate change impacts and emphasizes the need for further research in this area. Hanemann et al. (2006) conducted a scenario analysis of the economic cost of climate change impacts on California's water resources. Though the economic estimates are rough and tentative, they are significant and highlight the need for urgent implementation of appropriate mitigation and adaptation measures to minimize future losses. The main weakness of the study is that it considered only one specific emission scenario from one specific global climate model (the A2 emission scenario modeled using the Geophysical Fluid Dynamics Laboratory(GFDL) global climate model). The results from the study thus fall short of characterizing the uncertainty associated with the economic estimates, an issue of concern to decision makers and managers.

Despite their general appeal to decision makers, existing hydro-economic models have come under intense scrutiny for their inherent weaknesses (Young, 2004; Harou et al, 2009). Hydro-economic model objective functions commonly used typically seek to maximize expected net benefits. This risk neutral expression, however, ignores the desire of most decision makers to avoid severe consequences of extreme events. Synthesis of an otherwise complex multi-objective problem into a single economic objective is an inherent weakness in most of the past applications (Levy, 2004). Given the complexity of water resources management, decision processes should be guided by multi-objective tools that address all key stakeholder interests and management concerns beyond maximizing net economic benefits.

2.10 Overview of the Apalachicola-Chattahoochee-Flint Basin

The Apalachicola-Chattahoochee-Flint (ACF) basin covers an area of 19,800 square miles extending from its headwaters north of Lake Lanier to the Apalachicola Bay in Florida. Most of the basin lies in Georgia where more than 80% of water withdrawals take place (US Army Corps of Engineers, USACE, 1993). It covers 50 counties in Georgia, 10 counties in Alabama, and 8 counties in Florida (Figure 2.1). The basin is drained by three major rivers, i.e., the Chattahoochee, the Flint and the Apalachicola. The Chattahoochee River originates in the Blue Ridge Mountains of the Appalachian Highlands in northeast Georgia and drains an area of 8,770 square miles. The Flint River drains an area of 8,460 square miles originating from south of Atlanta all the way to Lake Seminole to the south where it joins the Chattahoochee River. The Apalachicola River drains an area of 2,370 square miles from the mouth of Lake Seminole south across northwest Florida to the Apalachicola Bay, where it finally discharges into the Gulf of

Mexico. The ACF River Basin is an important source of water for the three states, and plays a significant role in supporting socio-economic activities in the region. Over 70% of Georgia's population derives its water supply from the ACF basin, the majority of whom live in the Atlanta Metropolitan Area (AMA). The lower ACF also encompasses critical agricultural areas in Georgia and Alabama, and sustains the ecology and economy of the Apalachicola Bay.

The basin has a warm, humid, and temperate climate with mild winters and hot summers. The average annual precipitation over Georgia is 50 inches (1,250 mm) and varies from 45 inches (1,100 mm) in central Georgia to approximately 75 inches (1,900 mm) in the northeast corner of the state. The basin is vulnerable to droughts which are often associated with significant reduction in river flows and lake levels.

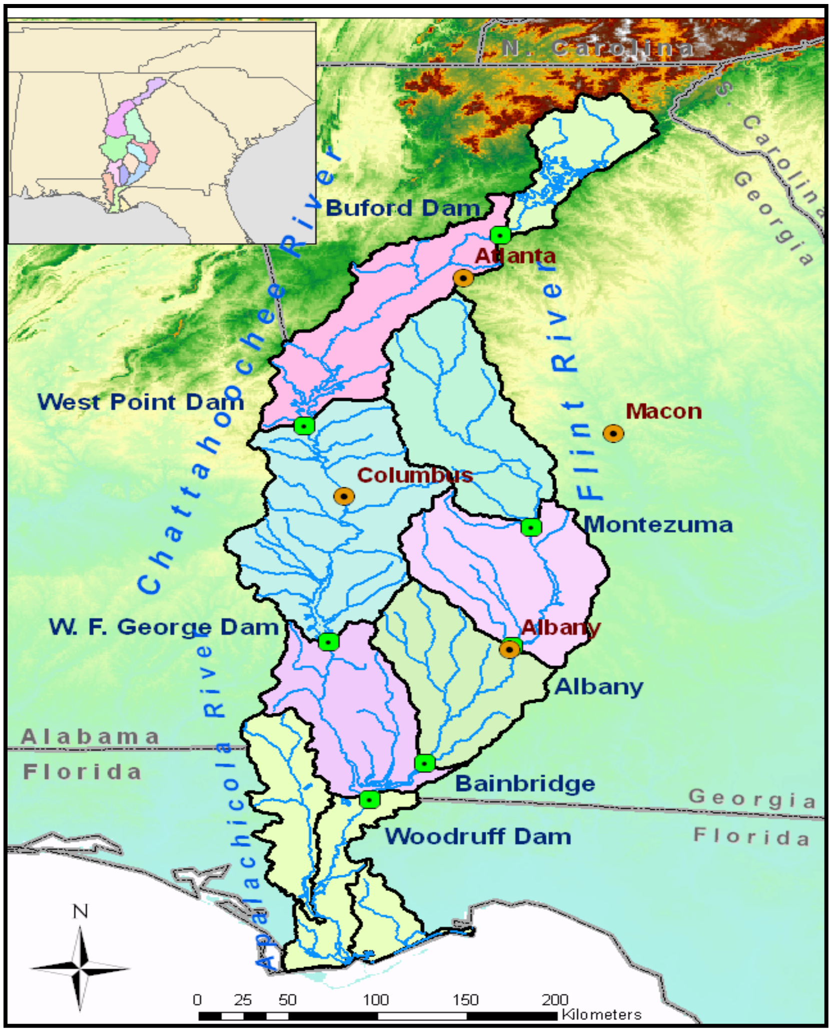


Figure 2.1: The Apalachicola-Chattahoochee-Flint River Basin

2.10.1 Current Water Status

The ACF basin is an important source of drinking water supply for the Atlanta Metropolitan Area (one of the fastest growing metropolitan areas in the US) and other smaller neighboring cities of Columbus and Albany in Georgia, and Dothan and Phenix City in Alabama. The upper Chattahoochee supplies more than 70% of the municipal and industrial water requirements for the Atlanta Metropolitan Area. The River also plays an important role in pollution abatement for the wastewater generated in the Metropolitan area. Besides drinking water supply, the ACF also serves critical water needs of other sectors including irrigation, industry, thermoelectric power cooling, navigation for barge traffic, recreational boating and fishing, aquatic biodiversity conservation, and hydropower generation. Seasonal flooding sustains forested flood plain ecosystems along the river corridor and provides the freshwater needed to maintain a healthy seafood industry in Apalachicola Bay.

2.10.1.1 Agricultural Water Use

The ACF basin water resources are the backbone to a vibrant agricultural sector in Georgia estimated to generate more than 50 billion dollars annually in direct and indirect economic benefits to the State (GWRI, 2010). Georgia is among the top states in the nation in total value of agricultural exports (No. 1 & 4 in Peanut and Cotton production respectively). More than 80% of irrigated agriculture takes place in the Flint River sub-basin south of the fall line, an area characterized by fertile arable soils. Figure 2.2 shows expansion of total irrigated land in Georgia over the past 40 years from about 150,000 acres in 1970 to about 1.5 million acres in 2009 (UGA CES, 2009). Cotton, corn, peanuts, soybeans, pecans, and vegetables are the most widely grown crops, accounting for more than 70% of the crops grown in the basin. Irrigation water use comprises about 90% of the water used during the April-September growing season (Georgia EPD, 2009). More than 70% of the irrigation relies on groundwater from the Floridian aquifer with less than 30% being irrigated from surface-water (Georgia EPD, 2006).

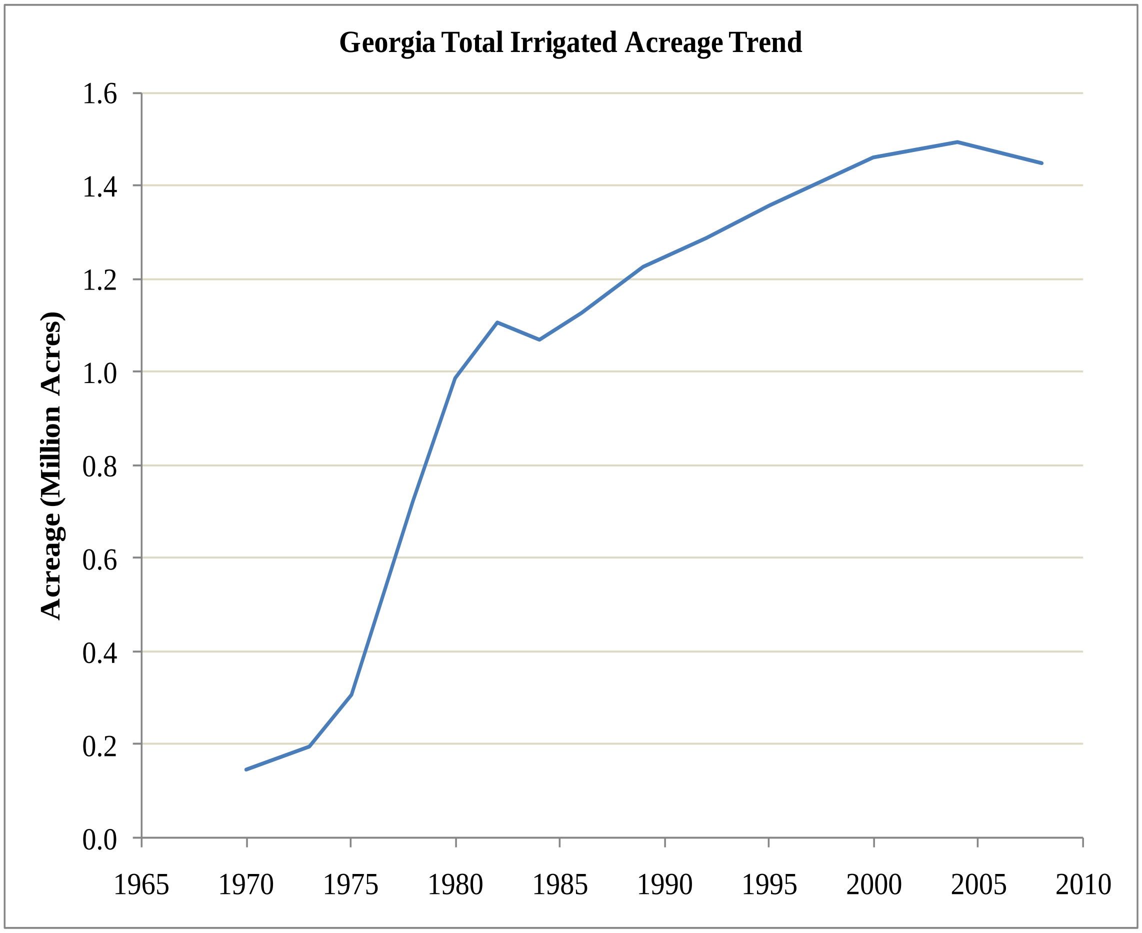


Figure 2.2: Georgia Irrigated Acreage Growth Trend

2.10.1.2 Thermal Energy Generation Cooling Water Requirements

Another significant off-stream water use in the basin is cooling water withdrawals for thermoelectric power generation at five existing plants (Yates, MacDonough, Wansley, Farley, and Scholtz). Of the total surface water withdrawals in the basin, about 60% are used in thermoelectric power generation. Although significant amounts of water are withdrawn for cooling purposes, only a very small percentage (about 1% to 5%) is consumed and the rest is returned to the river.

2.10.1.3 Hydropower Generation

Hydropower generation is an important instream water use sector in the basin. This takes place at four federal multipurpose reservoirs operated by the Corps of Engineers Mobile District (i.e., Buford Dam-105 MW; West Point Lake-82 MW; W.F. George-168 MW; and Woodruff-36 MW) and five private plants owned and operated by Southern Services (Morgan-16.8 MW; Bartlett's Ferry-173 MW; Goat Rock-26.3 MW; Oliver-60 MW; and North Highlands-29.6MW).

2.10.1.4 Recreation Water Use

Recreational water use contributes significantly to the local and regional economy of the basin. The upper ACF has a significant number of well developed and heavily used recreation facilities. Particularly, the Chattahoochee River sub-basin contains several heavily used reservoirs, national forests, and national and state parks. For example, Lake Sidney Lanier, located north of Atlanta, has more than 16 million visitors annually, and one of the highest visitation rates among U.S. Army Corps of Engineers reservoirs nationwide (USACE, 1989). Water related recreational activities include swimming, fishing, boating, camping, hiking, and photography. Recreational fishing is very popular on the Chattahoochee River and mainly consist s of cold-water trout fishery in the mountains above Lake Sidney Lanier and in the river below Buford Dam, where hypolimnetic releases provide cold water necessary for trout habitat. Lake Lanier also supports an active warm water fishery. Warm water recreational fisheries exist in the remainder of the Chattahoochee River sub-basin for various species of bass, catfish, and sunfish. Recreational fishing activities in West Point Lake, Lake Walter F. George, and

Lake Seminole support local, economically significant businesses and services, including bait and tackle shops, guide services, tournaments, hotels, and restaurants.

Recreational water use in the ACF basin contributes significantly to the local and regional economy of the basin. For example, according to USACE, in 2003 Lake Lanier registered 7,666,160 visitor days for a total economic benefit of 146.59 million dollars while in the same year, Lake West Point registered 2,264,600 visitor days and 37.47 million dollars.

2.10.1.5 Environmental Water Use

Maintenance of adequate water supplies for environmental conservation and sustainability of aquatic life is one of the most important water use requirements in the ACF basin. The basin provides habitat for 65 species listed as endangered or threatened under the Endangered Species Act, including four freshwater mussels and the gulf sturgeon (USFWS, 2009b). Recent surveys indicate that the number of species of freshwater mussels in the ACF basin has reduced from 29 to 22 in the past few decades. Of the remaining species, 5 are listed by the State of Georgia or the Federal Government as endangered or threatened (Livingston et al., 2000). The preservation of healthy ecosystems provides many benefits to the basin riparians including abundant fisheries, wildlife habitat, recreation, and clean water. Particularly, the basin sustains a very unique ecosystem and rich fishing industry in the Apalachicola Bay. The Bay is a highly productive barrier island estuary of state, federal, and international importance. The bay has been designated as a National Estuarine Research Reserve, Outstanding Florida Water, State Aquatic Preserve, and International Biosphere Reserve. The Bay’s ecosystem supports 131 freshwater and estuarine fish species and serves as a nursery for many significant Gulf of Mexico species. It is a source of about 90% of Florida's commercial oyster harvest, and the third largest shrimp catch in the nation (Whitfield and Beaumariage, 1977).

CHAPTER 3: METHODOLOGY

The proposed methodology has two main components, i.e., a water resources assessment component and an economic assessment component. A detailed discussion of the two components follows.

3.1 Water Resources Assessment Methodology

The water resources component comprises detailed hydrological and water resources assessment models that are used to simulate the spatial and temporal water availability in different parts of the basin subject to inflow variability and potential change, water use withdrawals and returns, and system constraints imposed by different management policies. The hydrological and water resources assessment methodologies used here are based on previous work on the development of a detailed Decision Support System (DSS) for the ACF basin (GWRI, 2008).

The ACF-DSS consists of a set of interlinked modules addressing a wide range of water related real-time operational, management and planning processes at different temporal and spatial scales. The linkages between the different modules enables horizontal and vertical consistency across all levels and ensures that system data, models, and outputs provide an integrative understanding of the overall system response. Figure 3.1 shows the ACF-DSS general modeling framework. The operational planning and management models address (i) turbine load dispatching for near real time operations (with an hourly time resolution over a horizon of one day), (ii) short range management (with hourly resolution over a horizon of one week), and (iii) long range planning (with a weekly resolution over a horizon of several months). The purpose of the assessment model is to evaluate infrastructure development options, demand scenarios, alternative forecasting models, impacts of climate variability and change, mitigation measures, and alternative management policies.

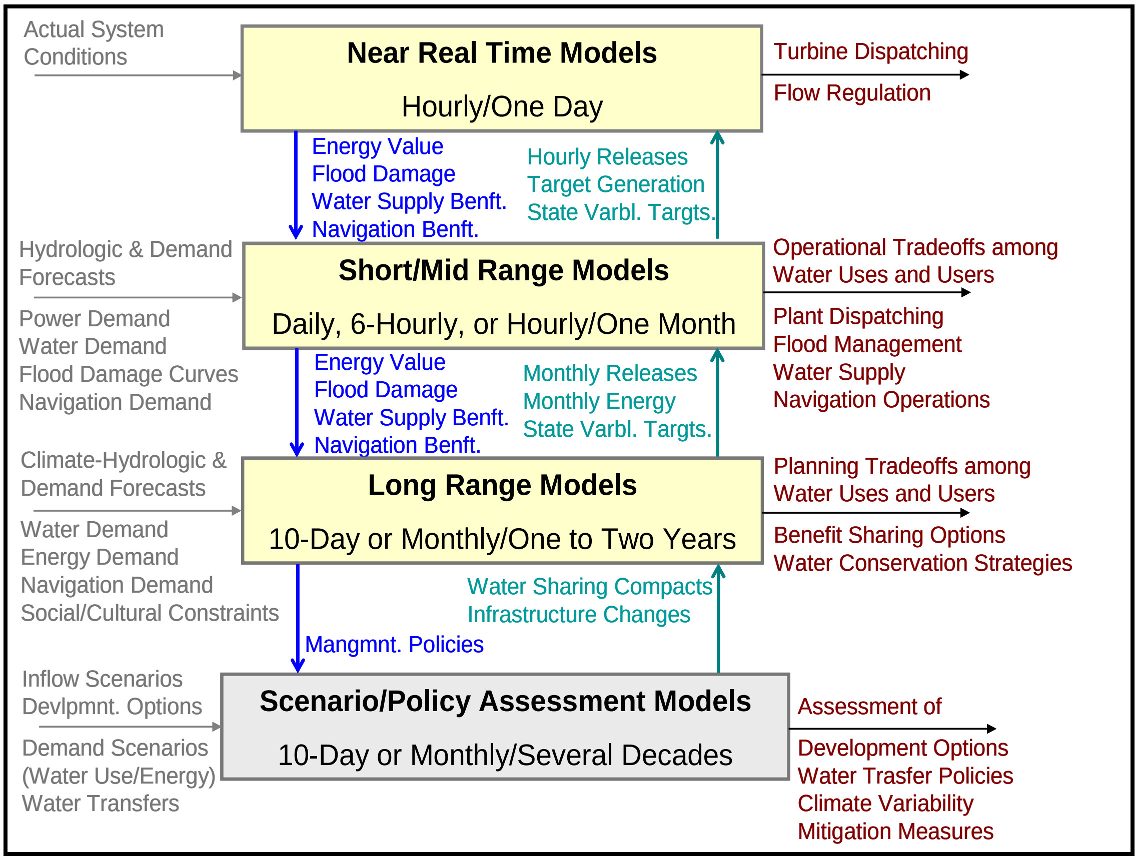


Figure 3.1: ACF DSS Modeling Framework (Source: GWRI, 2008).

3.1.1 Model Formulation

The general ACF-DSS formulation is summarized below:

Determine the control vector sequences, u(k)=0,1,2,…,N-1, that minimize the following performance index:

$$J = E\left\{\sum_{k=0}^{N-1}\begin{bmatrix} P_{spl}\left(u_{(k)}, S_{(k)}\right) + P_h\left(S_{(k)}\right) + P_{strg}\left(S_{(k)}\right) + \\ P_{utrg}\left(u_{(k)}\right) + P_h\left(S_{(N)}\right) + P_{strg}\left(S_{(N)}\right) \end{bmatrix}\right\}$$

Subject to:

the system dynamics,

$$S_i(k+1) = S_i(k) - e_i(k)A_i[S_i(k)] - u_i(k) + w_i(k) - D_i(k),$$
$$k = 0,1,...., N-1$$

and storage and release constraints,

$$S_i^{\min}(k) \le S_i(k) \le S_i^{\max}(k),$$
$$u_i^{\min}(k) \le u_i(k) \le u_i^{\max}(k),$$
$$k = 0,1,...., N$$

In the above expressions,

P_{spl} represents spillage from all reservoirs. This term is used to minimize spillage and thus maximize energy in the long run;

P_h is intended to keep reservoir elevations within their respective bounds, [H_{min}, H_{max}];

P_{strg} is intended to maintain reservoir levels near desirable sequences for example to ensure efficient energy generation and recreation activities; and

P_{utrg} ensures generation of reservoir releases which follow a certain desirable pattern.

The main ACF-DSS module used in this research is the scenario assessment module designed to evaluate infrastructure development options, demand scenarios, alternative forecasting models, impacts of climate variability and change, mitigation measures, and regulation policies. This model replicates the actual weekly operation of the ACF system under various hydrologic and demand scenarios and management policies. More specifically, at the beginning of each week of the simulation horizon, this component generates inflow forecasts; sets the water supply, energy generation, navigation, and flow reserve requirements; activates the long range optimization model to determines the most appropriate reservoir releases; simulates the response of the system for the upcoming week; and repeats this process at the beginning of the following week. At the completion of the forecast-decision-simulation process, the model generates sequences of all system performance measures including consumptive water demands at all nodes, weekly energy generation sequences at all generation facilities, reservoir levels, and inflow and release sequences for all storage facilities in the system. These sequences are used to compare the changes in the physical outputs of the system under alternative water management policies, demand changes, and climate change conditions. They are also used as inputs into the economic assessment models to generate the corresponding changes in economic benefits attributed to the policy, demand, and climate changes. A more comprehensive discussion of the ACF-DSS, including the detailed mathematical model formulations, can be found in GWRI (2008).

3.1.2 Input Data

The input data of the ACF-DSS includes water demand targets at different nodes; net basin supplies; reservoir release rules; reservoir storage and release limits; head loss functions; power load targets; hydro-turbine characteristics; tail-water curves; hourly power demand sequence; and environmental flow constraints.

3.1.2.1 Baseline and Projected Sectoral Water Demands

One of the major input data to the water resources assessment model (ACF DSS) are the aggregate water withdrawals and returns for each system node. These are computed from sectoral water withdrawal and return data generated from water use data for areas feeding into a specific node. The sectoral water withdrawal and return data used in this research was obtained from the Georgia Environment Protection Division (EPD). The data was originally developed through a comprehensive water resources assessment study for the ACT/ACF Basins (USACE, 1997) and has been updated and revised by the EPD over the years. The data set comprises of sectoral water uses (withdrawals/returns) for 2007 (Baseline year) and future water use projections for 2050. Detailed discussion of the methodology used to generate these data sets can be found in (USACE, 1997).

Figures 3.2 (a) and (b) show the baseline (2007) and projected (2050) average net water use, withdrawal, and returns for all the major system nodes. The largest withdrawals occur at the Atlanta node to meet the significant municipal water demand for the Metropolitan Atlanta area. The large return flow observed at the Whitesburg node is predominantly from the wastewater discharges from the Metropolitan Atlanta area. Water use by sector at each of the nodes is highlighted in Figure 3.3. Most of the irrigation water withdrawals occur at the Albany, Newton and Bainbridge nodes, all located on the Flint River. Withdrawals at Norcross and Woodruff are predominantly for industrial purposes. Based on the 2050 demand projections, the most significant increases in water withdrawals will occur at the Buford and Atlanta nodes, each node withdrawing about 230cfs above the 2007 withdrawals. These increases will be required to meet the significant municipal water demand growth anticipated for the Metropolitan Atlanta area. The projections indicate very mild increase (<20%) in irrigation withdrawals at Newton, Albany, and Bainbridge nodes. Overall, the anticipated growth in municipal and irrigation water demands for the entire basin is 60% and 4% respectively, with the former estimated to increase from 965cfs to 1545cfs and the latter from 367cfs to 381cfs. Increase in water withdrawal is expected to be matched by an even bigger increase in return flows resulting in a basin-wide net reduction in consumptive use from 1113cfs to 988cfs. Given the basin's limited water resources, the biggest challenge for water managers is how to meet the rapidly growing municipal water demand without compromising other water uses in the basin. This will require a multi-pronged integrated water resources management plan that addresses supply augmentation, improved water use efficiency, and adoption of effective demand management measures.

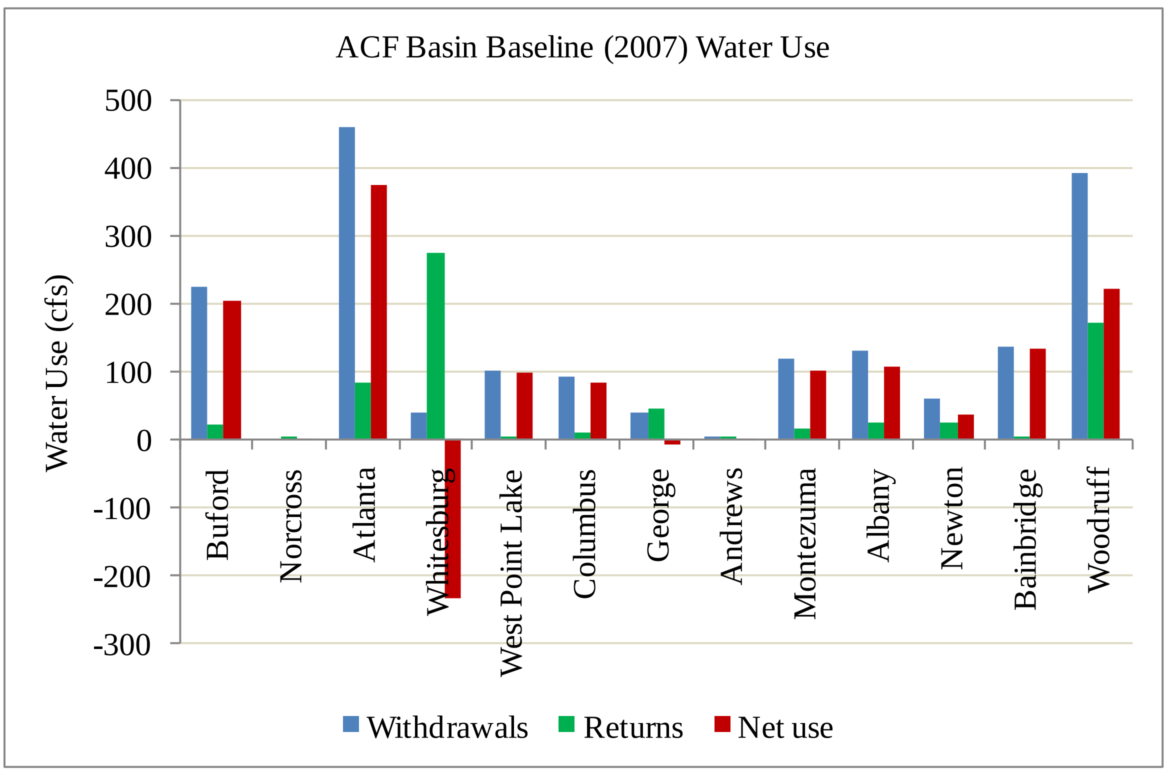


Figure 3.2 (a): ACF Basin Baseline Water Use

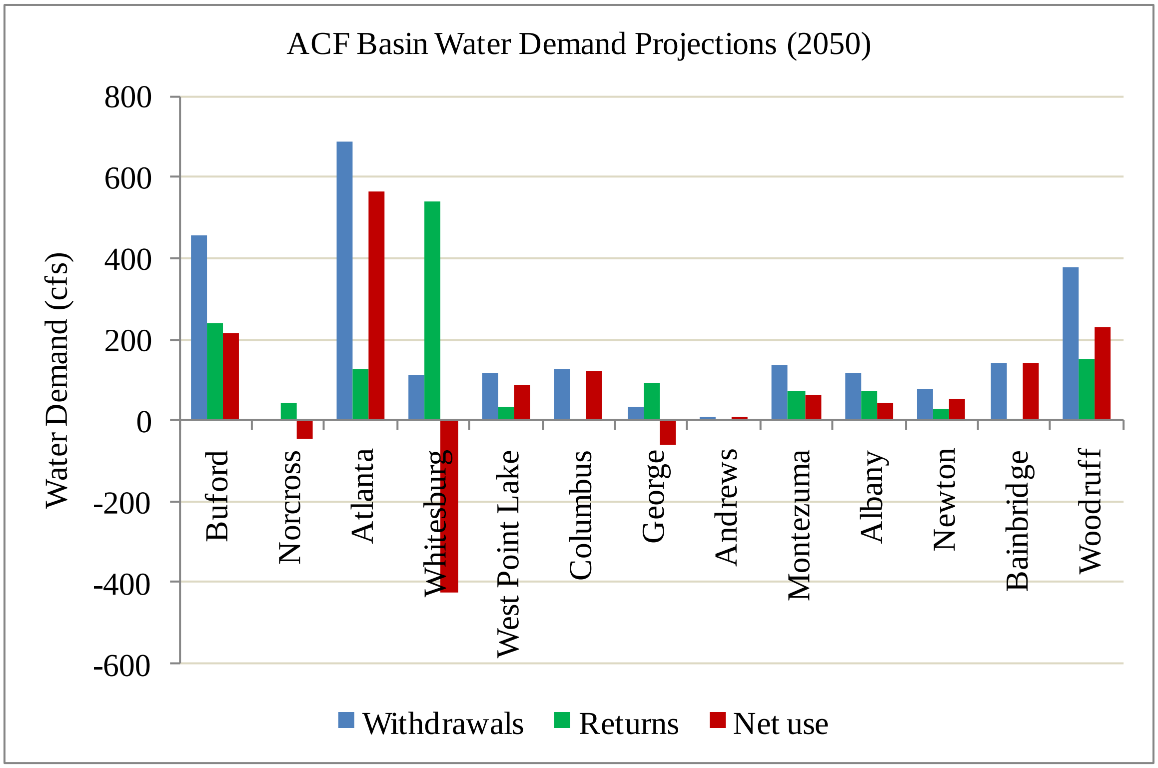


Figure 3.2 (b): ACF Basin Water Demand Projection (2050)

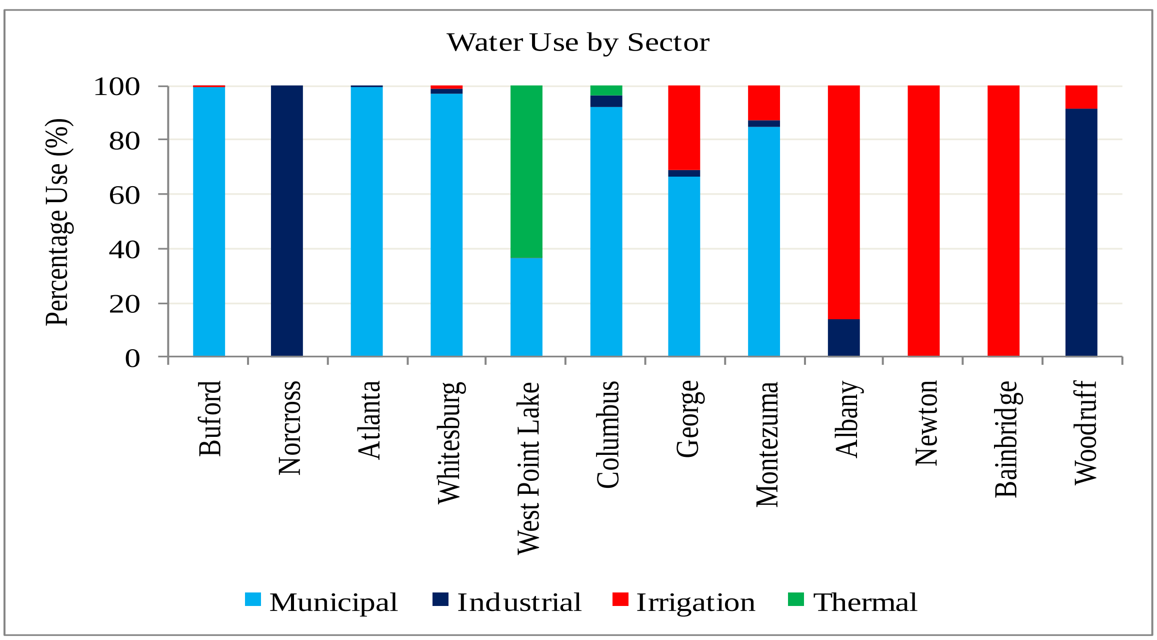


Figure 3.3: ACF Basin Water Use by Sector

3.1.3 Reservoir Operation Policies

Authority for management of the four federal reservoirs in the ACF basin is vested with the US Army Corps of Engineers who are mandated, through an Act of Congress, to coordinate operation of the facilities, on behalf of the Federal Government, to ensure achievement of their intended objectives. The original operation policy of the federal reservoirs was congressionally authorized and is outlined in the 1989 Draft Master Water Control Manual. According to the policy, the Corps of Engineers is required to utilize action zones to determine minimum hydropower generation, water supply and water quality releases at each project as well as maximum navigation releases from conservation storage while balancing the levels in all reservoirs. During low flow periods, the policy requires that water be taken first from storage in the lower reservoirs in the system and gradually pulling water from the upper reservoirs over time in accordance to the action zones. Following the severe drought of 2006, the Corps of Engineers revised its operational procedures and developed an Interim Operations Plan for the water storage facilities in the ACF Basin. This interim policy was revised again and will be referred to here as the Revised Interim Operation Policy (RIOP). The main purpose of the RIOP is to support the needs of the endangered Gulf sturgeon during the spring spawn and the needs of two protected mussel species in the summer. The RIOP specifies two parameters applicable to the daily releases from J. Woodruff Dam: a minimum discharge and a maximum fall rate. The minimum discharge from the Woodruff Dam is determined based on total basin inflow, month of the year, and composite basin storage. The composite storage is calculated by combining the storage of Lakes Lanier, West Point, and George. The storage of each individual reservoir is distinguished in four zones. These zones are determined by the operational rule curve for each project. The basin composite storage is also distinguished in four zones. As part of its ongoing research in the ACF basin, GWRI has developed an alternative reservoir operation policy (GTOP) that meets all the flow requirements for the endangered species required under the RIOP but also keeps the reservoir levels higher during drought periods. Detailed discussion of the two policies (RIOP and GTOP) is contained in Appendix A.

3.2 Economic Assessment Methodology

The economic assessment component comprises water valuation models used to derive economic benefits accruing to water use in different sectors (irrigation, thermal power cooling, hydropower, municipal, and recreation). Outputs from these models are used to provide policy insights and reveal opportunities for efficient and equitable water management and use. This research considers four important water use sectors: Agriculture, municipal, recreation, and energy generation (from hydro- and thermal plants). Environment water use is considered too, though to a limited extent, under water policy scenario assessments.

3.2.1 Valuation of Irrigation Water Use

Irrigation constitutes the highest consumptive water use in the ACF basin. Accurate valuation of irrigation water use is therefore of paramount importance to water managers and decision makers particularly in the analysis of economic tradeoffs with other competing water uses. The deductive approach is used based on an empirical valuation technique known as Positive Mathematical Programming (PMP), after Howitt (1995). The technique has been applied widely in the literature (Howitt et al. 2001, Howitt 2005, Howitt 2006, Howitt and Msangi 2006, Florencio-Cruz et al. 2002, Tsur et al. 2004, Henry de Frahan et al. 2007) and is among the most commonly used methods in irrigation water valuation. One of the key assumptions in using the method is that of a "profit maximizing farmer" who uses all the available information at his disposal (crop prices, input prices, climatic information, insurance, crop rotation, subsidies, and market trends) to make optimal production choices. The observed crop yield is assumed the best possible under the prevailing circumstances. The importance of this assumption is to ensure that the calibrated optimization model generates results similar to actual observed production levels. This strict calibration condition counters the main weakness in other commonly used models that fail to capture the true basis of the farmer's decision making process resulting in unrealistic model outputs. The premise here is that farmers optimize production taking into account factors that may be omitted from a conventional model. Once the model is calibrated to actual farmer behavior and production output, it can be used for policy analysis as a predictive tool to assess farmer behavior under different conditions (of climate and input and output prices).

3.2.1.1 Model Formulation

The first step in the model formulation process is to define the underlying production function that closely represents the relationship between inputs and outputs in the crop production process. The model development process then proceeds in a three step procedure i.e., (a) model calibration, (b) parameterization of a quadratic land cost function and the crop production function, and (c) formulation of non-linear profit maximization objective function. Once the model has been calibrated, deriving a demand curve involves running the model with different available quantities of water, each time noting the shadow price of water.

3.2.1.1.1 Definition of Production Function

The following Constant Elasticity of Substitution (CES) production function is used in this research, following parameterization suggested in Howitt (2006):

$$Y_{gi} = \tau_{gi} \left[\sum_{j} \beta_{gij} X_{gij}^{\rho_i} \right]^{\nu / \rho_i}$$

In the above expression, subscript g refers to specific agricultural zones (county or sub-basin); i refers to irrigated crop types (Corn, Cotton, Beans, Peanuts); and j refers to crop production inputs (land, water, labor, supplies, and machinery). Y refers to crop output in metric tons and X refers to production input usage. The relative use of production inputs is represented by the share parameter ß, while τ is a scale parameter, and ν is the returns to scale coefficient. Parameter ρ is computed using equation $\rho_i = (\sigma_i - 1)/\sigma_i$, where σ_i is the elasticity of substitution of crop i.

3.2.1.1.2 Model Calibration

A constrained linear programming production problem is solved to generate a vector of shadow prices[2] for constrained production inputs and for the amount of land allocated to each crop in each agricultural production zone. The Constrained Linear Production problem is defined as follows:

[2] *Shadow price* is the change in the objective value of the optimal solution of an optimization problem obtained by relaxing the constraint by one unit.

$$
Max\,\Pi = \sum_{g}\sum_{i}\left[p_{gi}y_{gi} - \sum_{j}\omega_{gij}a_{gij}\right]x_{gi,land}
$$

$$
subject\ to:
$$

$$
\sum_{i} a_{gij}x_{gi,land} \le b_{gj} : \forall g, j
$$

$$
x_{gi,land} \le \breve{x}_{gi,land} + \varepsilon : \forall g, j
$$

The subscripts g, i, and j are as defined above. Decision variable, x_{gi}, represents land use for crop i in region g; y is the crop yield in metric tons; p is the marginal revenue per ton of crop i in region g; ω_a represents the average variable costs per acre of land, where the coefficients, a, are given by the ratio of total factor usage to land. Parameter b is the regional limit on resource j. In addition to the traditional resource and non-negativity constraints, a set of calibration constraints is added to restrict land use to observed values. The variable $\tilde{x}_{gi,land}$ is the observed value of resource usage and ε is small perturbation that decouples the resource and calibration constraints. The solution to the LP problem yields a vector of shadow prices for constrained production inputs and for the amount of land allocated to each crop in each region g. The shadow values from the land calibration constraints represent the additional implicit costs that are required for the marginal conditions of optimization on land allocation to hold across crops.

3.2.1.1.3 Parameterization of Land Cost Function and Crop Production Function

Parameterization of the quadratic land cost function and crop production function is based on the shadow values derived above. LaGrange multipliers from the binding calibration constraints are used to estimate slope and intercept of the linear marginal cost function.

$$C_{gi} = \alpha_{gi} x_{gi,land} + 0.5\gamma_{gi} x_{gi,land}^2$$

The parameters α_{gij} and γ_{gij}, corresponding to the intercept and slope of a linear marginal cost function, are computed as follows:

$$\gamma_{gi} = \frac{2\lambda_{2,gi,land}}{\tilde{x}_{gi,land}}$$

$$\alpha_{gi} = \sum_j a_{gij}\omega_{gij} - 0.5\gamma_{gi}\tilde{x}_{gi,land}$$

where $\lambda_{2,gi,land}$ is the dual value of the binding calibration constraint on land computed from the linear production problem.

The parameters of the crop production function are computed using the following equations (after Medellín-Azuara, 2006):

$$\beta_{gi1} = \frac{1}{1 + \left(\frac{x_{gi1}^{-1/\sigma_i}}{\omega_{gi1}} \sum_{j \neq 1} \frac{x_{gij}^{-1/\sigma_i}}{\omega_{gij}} \right)} \; and \; ; \beta_{gij;j\neq 1} = \frac{1}{1 + \left(\frac{x_{gi1}^{-1/\sigma_i}}{\omega_{gi1}} \sum_{j \neq 1} \frac{x_{gij}^{-1/\sigma_i}}{\omega_{gij}} \right)} \left(\frac{\omega_{gij} x_{gi1}^{-1/\sigma_i}}{\omega_{gi1} x_{gij}^{-1/\sigma_i}} \right)$$

$$\tau_{gi} = \frac{y_{gi} x_{gi,land}}{\left[\sum_j \beta_{gij} X_{gij}^{\rho_i} \right]^{\frac{v}{\rho_i}}}$$

3.2.1.1.4 Formulation of non-linear profit maximization objective function

The calibrated production and land cost functions are used in formulating the required non-linear profit maximization problem defined as follows:

$$Max \prod = \sum_g \sum_i \left[p_{gi} \left(\tau_{gi} \left[\sum_j \beta_{gij} x_{gij}^{\rho_i} \right]^{v/\rho_i} \right) - \left((\alpha_{gi} + 0.5\gamma_{gi} x_{gi,land}) + \sum_{j \neq Land} \omega_{gij} a_{gij} \right) \right] x_{gi,land}$$

$$S.t.$$

$$\sum_i a_{gij} x_{gi,land} \leq b_{gj} \forall g, j \in \{Land, Water\}$$

$$\sum_t x_{g,water,t} \leq \xi b_{g,Water} \forall g$$

The last constraint above is for aggregate water supply for a agricultural zone g for all months in a water-year, where $b_{g,water}$ is the observed water use for the zone. Parameter ξ is used to obtain shadow values of water by constraining regional water, such that $0<\xi<1$. The model is solved for each of a number of increments/reduction of water supply (by varying parameter ξ) and the net return to each increment/reduction of water derived from the incremental change in the objective function (Bernardo et al., 1987). The net return provides an estimate of the value of water for the supply scenario assumed for that solution. The marginal benefit function can then be determined from the series of net return values.

3.2.1.2 Model Application for the Flint Sub-basin

The model is applied to the Flint River sub-basin where more than 80% of irrigated agriculture in the ACF basin takes place. The Flint River is one of the three major rivers of the ACF. The river drains an area of 8,460 square miles from Atlanta to Lake Seminole where it joins the Chattahoochee River. The sub-basin stretches across 42 counties, entirely within the boundaries of Georgia. The river has only two major impoundments: Lake Blackshear, near Warwick, and Lake Worth, near Albany. Figure 3.4 shows the geographical extent of the Flint sub-basin. Average annual rainfall over this sub-basin ranges from 48 to 54 in/yr, most of which falls between early November and mid-April. Agriculture is one of the most important economic sectors, most of which depends heavily on supplemental irrigation. The agriculture sector contributes about $ 6 billion in direct and indirect economic benefits to the sub-basin's economy. Irrigated land has significantly expanded over the past 40 years from about 150,000 acres in 1970 to about 1.5 million acres in 2009 (UGA CES, 2009). Cotton, corn, peanuts, soybeans, pecans, and vegetables are the most widely grown crops, accounting for more than 70% of the crops grown. Irrigation water use comprises about 90% of the water used during the April-September growing season (Georgia EPD, 2009). More than 70% of the irrigation (403,000 acres) relies on groundwater from the Floridan aquifer with only 160,000 acres being irrigated from surface-water (Georgia EPD, 2006). Irrigation withdrawals vary significantly throughout the year with most of it taking place between April and September, the growing season for major row and forage crops. Irrigation water withdrawals usually peak in June-August, corresponding to the most critical development stage for the major forage and row crops and when the weather is the hottest. During this period, up to 950 mgd and 250 mgd are withdrawn from groundwater and surface water respectively, in a typical drought year. The irrigation amounts vary widely depending on soil type, crop type, stage of crop development, irrigation system type, temperature and rainfall, availability of water, and climatic conditions (wet, average, or dry year). The highest concentration of irrigation in the sub-basin is in the lower Flint and Spring Creek areas. The Ichawaynochaway sub-basin is equally divided between ground-water and surface-water. The middle Flint and Kinchafoone-Muckalee Creek sub-basins have lesser amounts of land under irrigation.

Figure 3.4: The Flint River Sub-basin (Source: USGS, 2011)

3.2.1.2.1 Input Data

Several data types are required as inputs to the model, i.e., irrigated and rainfed crop acreages, production inputs factor usage (labor, supplies, water, machinery, and land), market price of crops, and input factors. The crops considered in this study include corn, cotton, and peanuts, which account for more than 70% of the total irrigated acreage in the sub-basin (Figure 3.5). Year 2007 was selected as the base year for factor usage and crop and input prices. Five production factors are considered, namely, land, water, labor, machinery, and supplies. With the exception of water and land, the factor usage (per acre) for the other three factors was assumed to be the same for both production zones. Thus implicitly, heterogeneity in production at the zone level is addressed through different land and water usage, crop mix, and corresponding yield.

The main data source was the USDA's National Agricultural Statistics Service (NASS). USDA conducts several surveys annually on different aspects of US agriculture including, among others, crop yield, production output and input prices, production input factor usage, and changes in production trends in different US regions. Information from the following USDA surveys was particularly important: National Agricultural Census, National Irrigation Survey, National Agricultural Yield Survey, and County Agricultural Production Survey. Additional data and information was obtained from reports on various surveys conducted under the University of Georgia Cooperative Extension Services Program.

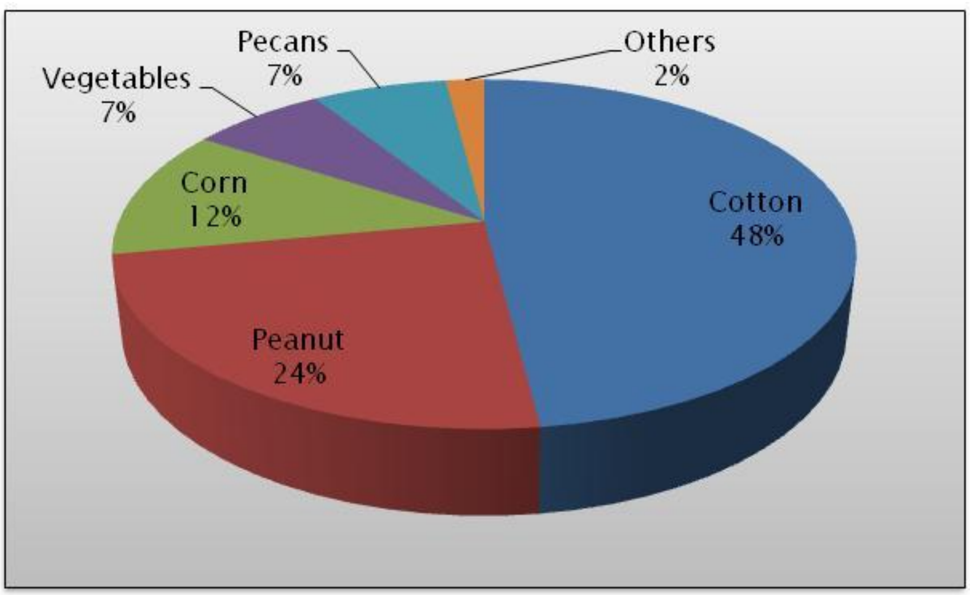


Figure 3.5: Major Irrigated Crops in the Flint Sub-basin.

3.2.1.2.2 Model Application

The non-linear profit maximization problem was solved for each production zone (Lower and Upper Flint), several times each corresponding to a different water constraint, each time noting the shadow value of water (willingness to pay). The shadow values were used to derive the required irrigation water demand curve. Figures 3.6 (a) and (b) show the irrigation water demand curves for Lower and Upper Flint respectively for typical dry and normal years. Irrigation water value is much higher during dry years compared to normal years. For example for an irrigation water supply level of 317cfs, the irrigation water value ranges from about $ 3.8 to $ 100 per acre-foot for a typical normal and dry year respectively. This difference in value is expected because the demand for irrigation water is much higher during the dry years and farmers are willing to pay more for water compared to a normal year when the rains are good and demand for irrigation water is much lower. Comparison of the demand functions for the Upper and Lower Flint shows that farmers in the Upper Flint are willing to pay more for an acre-foot of water than those in the Lower Flint. For example, at 50% deficit in irrigation water demand, farmers are willing to pay $ 200 and $ 150 per acre-foot of water in the Upper and Lower Flint respectively. This is consistent with the conditions in the two sub-basins. Water is scarcer and the productivity of the soils is much lower in the Upper Flint compared to the Lower Flint which is endowed with good groundwater potential and fertile soils.

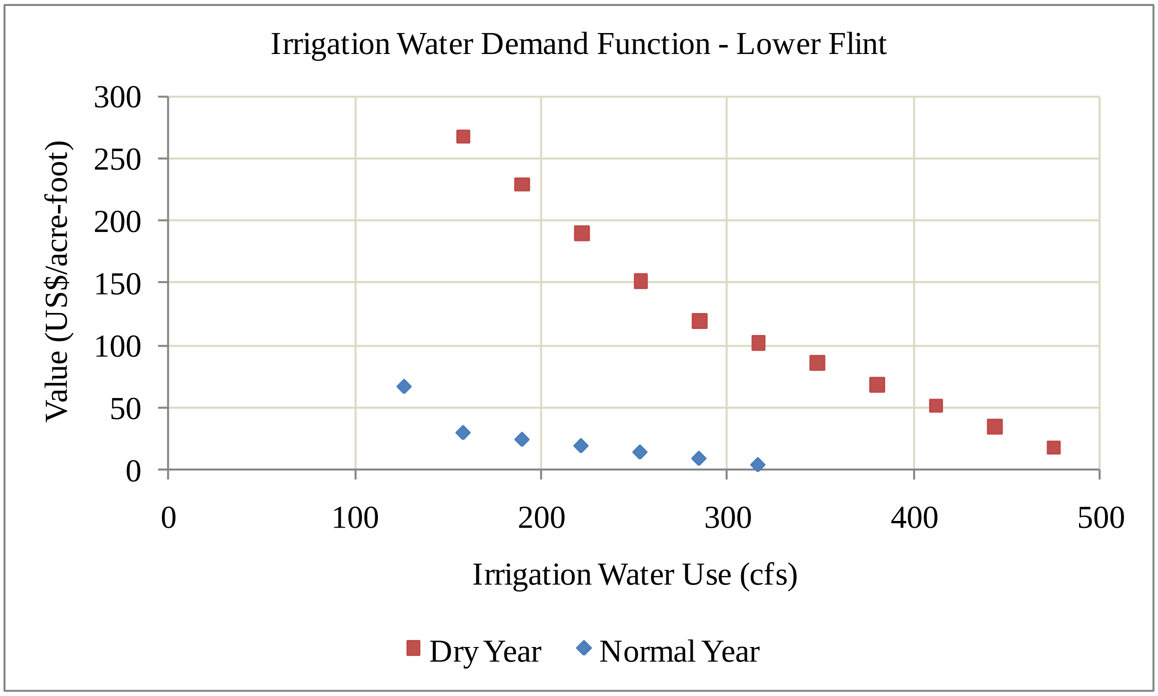


Figure 3.6 (a) Lower Flint Irrigation Water Demand Function

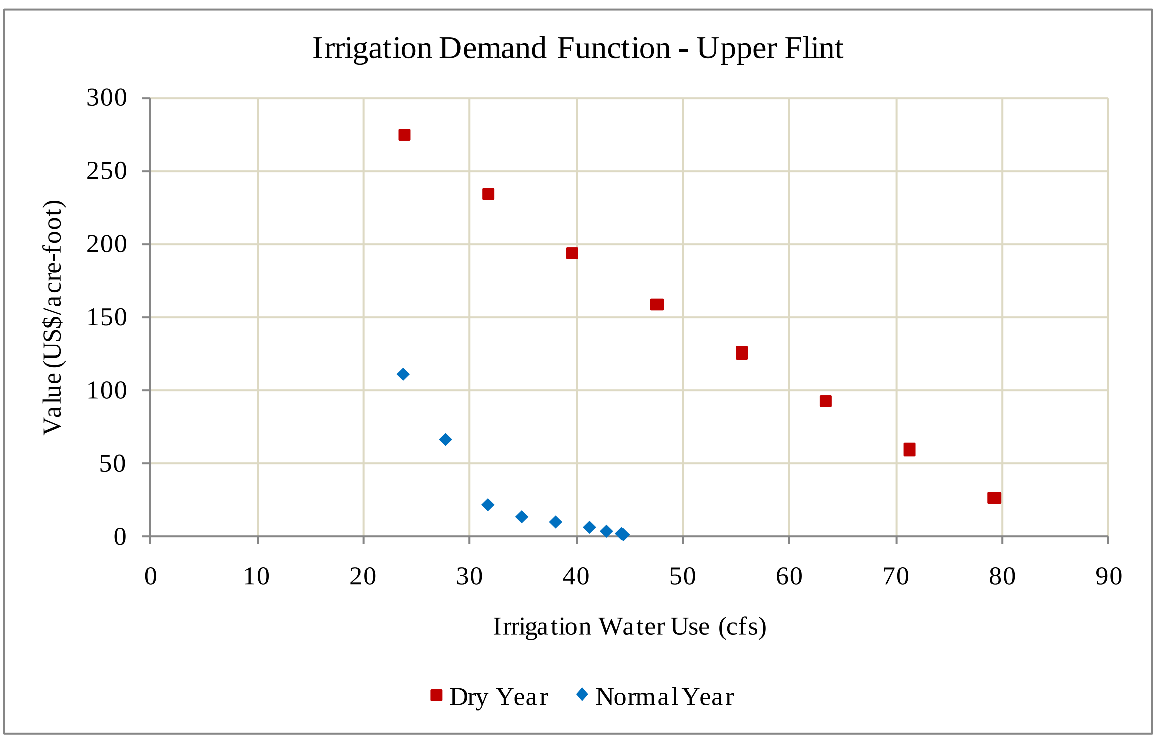


Figure 3.6 (b): Upper Flint Irrigation Water Demand Function

3.2.2 Valuation of Municipal Water Use

Municipal water use comprises water use in residential settings (inside and outside), commercial entities (public and private business premises), government institutions (e.g., public offices, schools, hospitals, and security and other agencies), and other public services (including irrigation and care of public recreational facilities). Though it would be preferable to analyze water use by each individual category separately, it is often difficult to obtain disaggregated data isolating other municipal customers from residential uses. Most studies therefore tend to focus on either residential water use or the total of municipal consumption. Economic valuation of municipal water use is based on the well established economic concept of willingness to pay (WTP).

3.2.2.1 <u>Model Formulation</u>

The municipal water valuation is based on observed municipal water supply quantities and corresponding prices and price elasticity of demand for residential water (estimated from secondary studies). This approach has been used widely by several authors to develop water demand functions and values for various levels of water shortage in many parts of the world. Hanemann (1998) provides an extensive review of the theory and application of residential water demand analysis from several publications in the United States on the subject.

3.2.2.1.1 Municipal Water Demand Curve

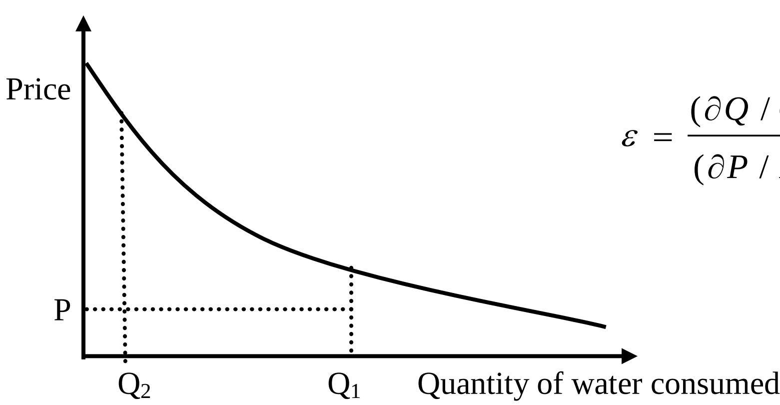
Estimating consumer surplus requires a demand curve. In the absence of a market demand curve for municipal water supply, an approximation is usually developed. The approximate demand function is obtained by assuming a functional form and inferring an empirical demand function from an observed price-quantity point on that function.

Several functional forms have been used in past studies including Constant Elasticity (Wade and Roach, 2003), Cobb-Douglas and Translog (Griffin, 1990). The functional form used in this research is the Constant Elasticity demand function. This function is a more realistic representation of municipal water consumer behavior because it allows prices to increase at an increasing rate with increasing scarcity levels (Young, 2005). Wade and Roach (2003) used the Constant Elasticity demand function to estimate economic benefits of municipal and industrial water supply reliability for Metropolitan Atlanta. They assumed a single point elasticity of demand estimate of –0.16 for the Metropolitan Atlanta area.

The Constant Elasticity demand function is given by the equation:

$$Q = \alpha P^{\varepsilon}$$

where Q is the quantity of water consumed, P is the price of water, and ε is the price elasticity of demand. The change in consumer surplus associated with a reduction in water supplies from Q_1 to Q_2 is computed as the integral of the area under the demand curve shown in the Figure 3.7.



$$\varepsilon = \frac{(\partial Q / Q)}{(\partial P / P)}$$

Figure 3.7: Constant Elasticity Demand Function

Young and Gray (1972) developed a standard formula for the integral of a constant elasticity demand function to estimate an at-source value of residential water. The demand equation (1) is integrated to get the change in consumer surplus (CS) corresponding to a reduction in *at-site* water consumption from Q_1 to Q_2.

$$CS_{at-site} = \frac{PQ_1^{\frac{1}{\varepsilon}}(Q_2^{1-\frac{1}{\varepsilon}} - Q_1^{1-\frac{1}{\varepsilon}})}{(1-\frac{1}{\varepsilon})}$$

The equation above represents the economic value consumers attach to a reduction in water supply from Q_1 to Q_2. It should be noted that this is the value of treated water delivered to the final point of consumption. However, for purposes of comparison with instream water uses or raw water used in other off stream uses, it is important to estimate at-source municipal water values. To estimate the net *at-source* change in consumer surplus ($CS_{at\text{-}source}$), we have to account for the variable costs of water production, treatment, transmission, and distribution. We also have to account for the non-revenue water (i.e., water losses). The net at-source change in consumer surplus is estimated by subtracting the variable and non-revenue water costs from the at-site change in consumer surplus ($CS_{at\text{-}site}$):

$$CS_{at-source} = (1-\alpha)\left(\left[\frac{P_1 Q_1^{\frac{1}{\varepsilon}}(Q_2^{1-\frac{1}{\varepsilon}} - Q_1^{1-\frac{1}{\varepsilon}})}{(1-\frac{1}{\varepsilon})}\right] - \left[P_1(Q_1 - Q_2)\right]\right)$$

$CS_{at\text{-}source}$ is the value of raw municipal water, also considered to be the net benefit, which is compared with raw water values in other uses like irrigation, hydropower, and recreation.

3.2.2.1.2 Price Elasticity of Demand

Planning and Management Consultants, Ltd. (PMCL) estimated ACF/ACT demand elasticity within the ACF/ACT Comprehensive Study (PMCL, 1996, Volume II). They recommend an elasticity estimate of –0.2 for the ACF basin, which is typical for water which is a good with no close substitute and small income elasticity. This is the value used in this research and is assumed to remain constant over the relevant range of municipal water consumption for the study area. Renwick and Green (2000) report a long run –0.16 price elasticity in recent research done in California. The California Department of Water Resources adopted Renwick's research as the basis for assuming single-family residential price elasticity of –0.1 for winter months and –0.2 for summer months. Young (2005) suggests –0.2 to –0.6 as a plausible range of price elasticity of demand for municipal water use in the United States, signifying an inelastic demand that is generally price responsive.

3.2.2.2 Model Application – Metropolitan North Georgia Water Planning District

The model was applied to the Metropolitan North Georgia Water Planning District (MNGWPD) as a case study. MNGWPD consists of metro Atlanta and the surrounding 16 counties of Bartow, Cherokee, Clayton, Cobb, Coweta, DeKalb, Douglas, Fayette, Fulton, Forsyth, Gwinnett, Hall, Henry, Paulding, and Rockdale. The District is situated within the upstream headwaters of 5 river basins: Chattahoochee, Etowah, Flint, Oconee, Ocmulgee, and Tallapoosa. Of these, only the Chattahoochee and Flint sub-basins fall within the ACF basin. The District has a population of 4.0 million, about 50% of Georgia's population. The Metro Water District relies primarily on surface water from rivers and storage reservoirs as its main source of water supply. About 72% of the supplies are from the Chattahoochee sub-basin, which includes Lake Lanier, while 28% are from the remaining five sub-basins. The District has a total of about 888 AAA-MGD (Average Annual day-Million Gallons per Day) of permitted supplies, 99% of which is surface water and 1% groundwater. The District currently has 38 publicly-owned surface water treatment plants, ranging in permitted capacity of less than 1 MGD to 150 PD-MGD (peak day - million gallons per day), providing a combined permitted treatment capacity of 1135 PD-MGD (710 AAD-MGD). More than 65% of the municipal water withdrawals return to the system as return flow. Residential and commercial sectors are the dominant water use categories accounting for more than 75% of the total water use in the District (Figure 3.8). Water consumption in the 16 counties varies widely as shown in Figure 3.9.

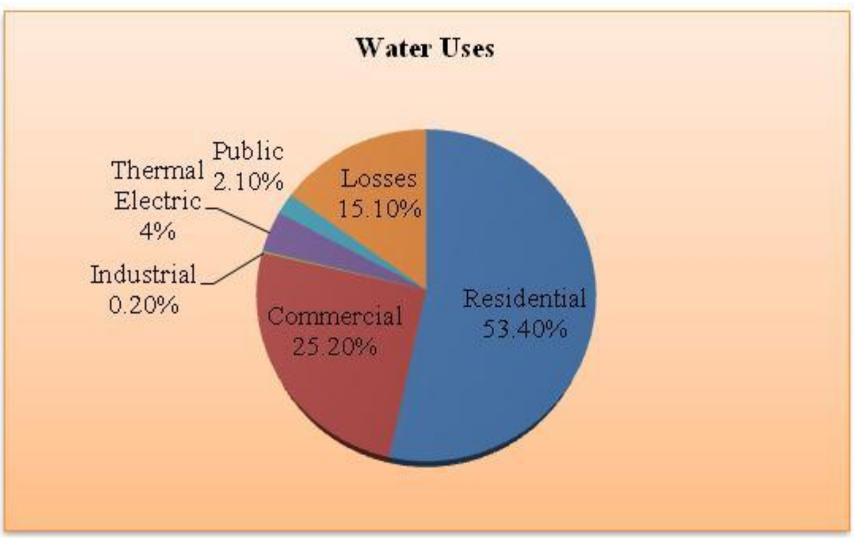


Figure 3.8: Water Use Categories in Metro North Georgia Water District

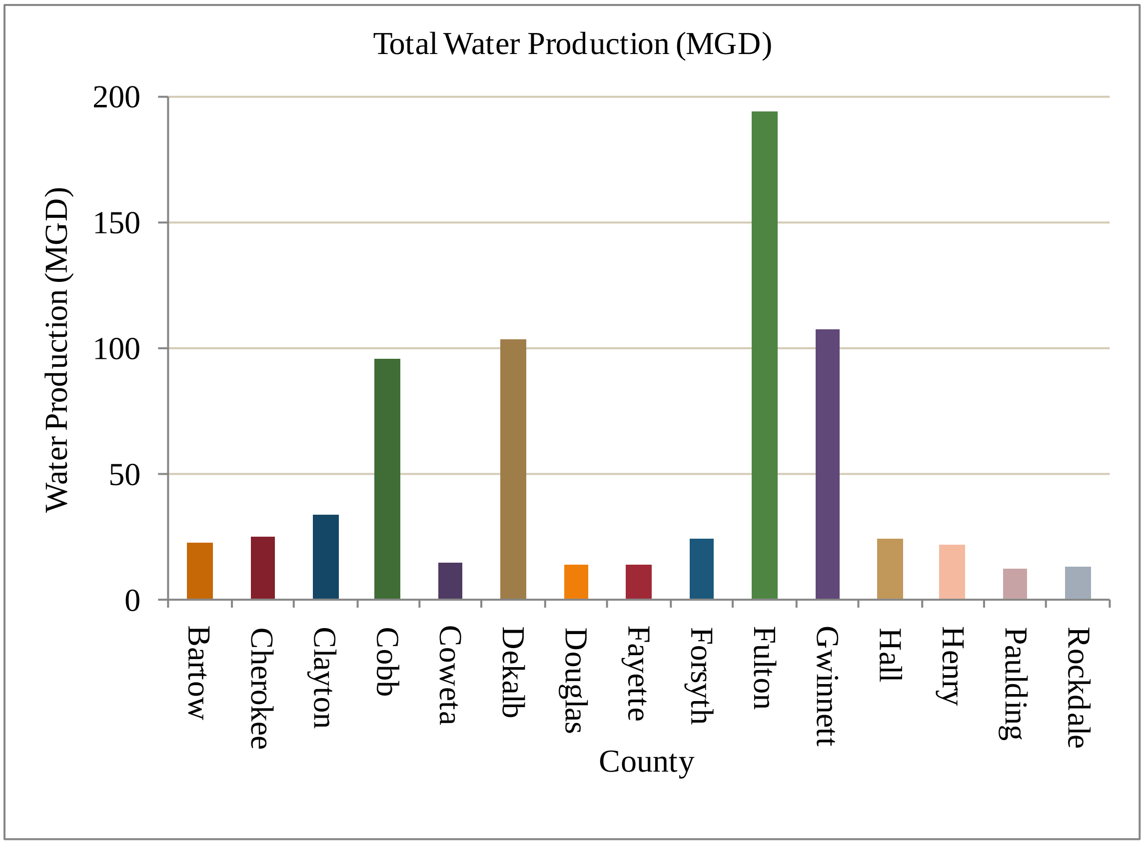


Figure 3.9: Municipal Water Use by County

3.2.2.2.1 Water Demand Forecasts

The MNGWP District Water Supply and Water Conservation Management Plan (2009) gives details of water demand forecasts for each of the 16 counties in the district. The Plan also contains specific water conservation measures to be implemented in the district to increase water use efficiency and reduce water consumption. The measures include, among others, aggressive leak detection and repair program, water re-use, toilet rebate program, and tiered water rates. Details of the proposed conservation measures and their status of implementation are contained in the MNGWP District Water Supply and Water Conservation Management Plan (2009). Figure 3.10 shows the projected water demands for the different counties in the district for 2035 and 2050. With implementation of the enhanced water conservation program, the District's water demand is estimated to exceed 1000 AAD-MGD by 2035. To meet the projected future water supply needs, there will be need for expansion of existing water sources and development of additional new water supply sources. To this end, the Plan proposes three key focus areas: (a) an aggressive water conservation program, (b) maximization of existing supply sources, and (c) new supply sources through new reservoirs.

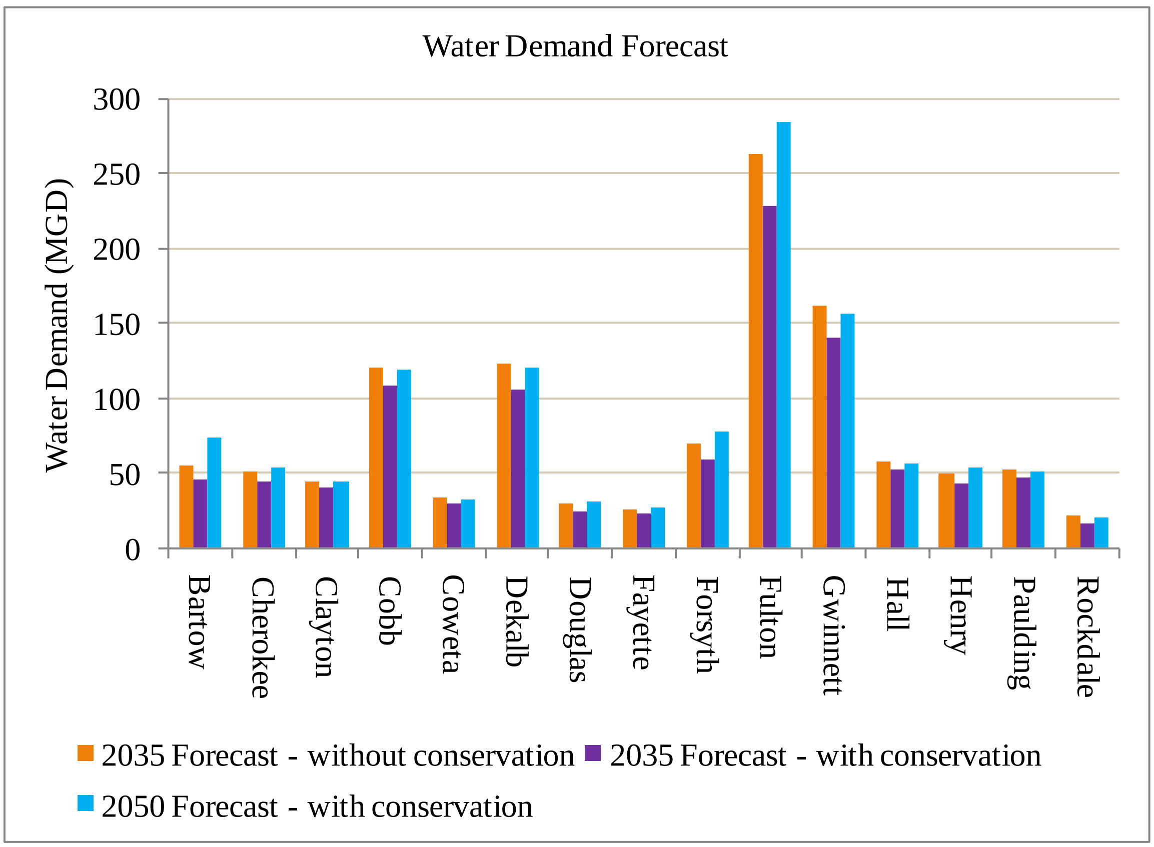


Figure 3.10: Water Demand Forecast by County

3.2.2.2.2 Municipal Water Demand Curve

Equation 3 is solved for different water supply levels (Q2) to derive the municipal water aggregate demand curve for MNGWPD shown in Figure 3.11. The figure shows increasing consumer willingness to pay corresponding to increasing water scarcity. For example, a 50% reduction in water supply is associated with an increase in willingness to pay from $ 4.4 to $ 32.5 per 1000 gal.

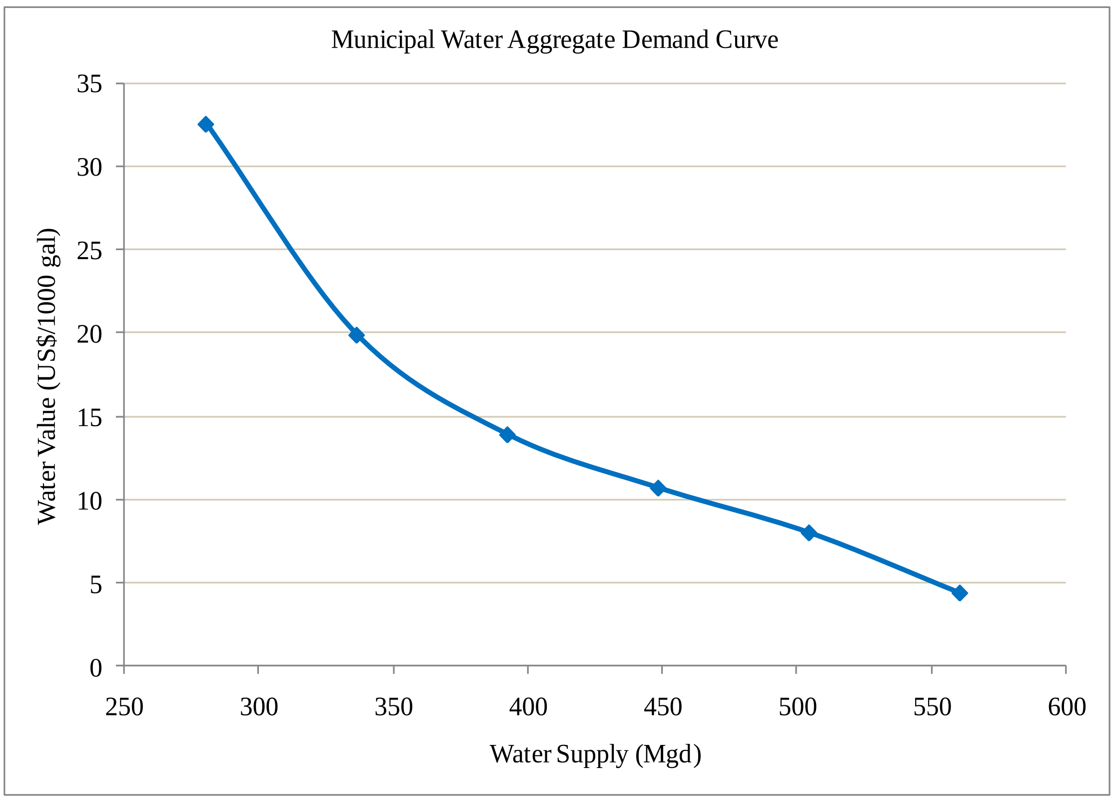


Figure 3.11: Municipal Water Demand Function

3.2.3 Valuation of Energy Generation Water Use

During energy generation, water is either used directly to run turbines during hydropower generation or indirectly as cooling water requirements in thermal power generation. Valuation of water use in these two cases is discussed below.

3.2.3.1 Hydropower Generation

The methodology used for economic valuation of water use in hydropower generation is based on the cost avoided by utilities in substituting hydropower for the more expensive alternative power generation technologies. It is therefore not necessary to derive a demand function for hydropower generation water use since the marginal value of water in this case depends on the cost of alternative power and not necessarily on quantity of water available for hydropower generation.

3.2.3.1.1 Model Formulation

Valuation of water for hydropower generation follows two steps. First, the value of electricity produced from a specific hydro plant is determined using the alternative cost technique, based on an estimate of the cost of the next likely alternative source of electrical power. The residual approach is then used to estimate the portion of the total value of electricity output attributable to the water used for generation. The water valuation model is represented by the following equation:

$$\begin{aligned} B_{hyd} &= Benefits(Energy + Capacity) - Costs(Variable + Fixed) \\ &= (P_{En}.MWH + P_{Cap}.MW) - (C_{Var}.MWH + C_{Fixed}.MW) \end{aligned}$$

where B_{hyd} denotes net benefits ($), P_{En} energy price ($/MWH), P_{Cap} capacity price ($/MW), C_{Var} variable (O&M) costs ($/MWH), and C_{Fixed} fixed (capital recovery) costs ($/MW).

Input data required by the hydropower economic model include: weekly energy generation sequences from the water resources assessment mode; capital recovery costs; operation and maintenance costs; energy and capacity prices from different sources (Energy Information Administration, SEPA, Georgia Power, and Department of Energy).

3.2.3.2 Thermal Energy Cooling Water

Development of the economic demand function for cooling water is based on the cost of alternative cooling technologies. The most commonly used cooling technologies in the ACF basin include: once-through cooling systems, cooling ponds, wet tower cooling, dry tower cooling, and hybrid wet/dry cooling towers. The Dry cooling technology is used as the alternative to wet cooling in assessing the economic value of cooling water use in thermal power generation.

3.2.3.2.1 Model Formulation

The total demand function is derived from estimated avoided costs of more expensive dry-cooling technology instead of the currently used water based cooling technology. It is estimated by the capital plus variable costs of the dry cooling technology, minus the capital plus variable costs of wet cooling technology.

$$B_{therm} = \frac{\Delta C_{En}}{\theta} = \frac{(\alpha(K_{dry} - K_{wet})MW + (OM_{dry} - OM_{wet}))}{\theta \; MWH}$$

where ΔC_{En} is increase in cost of energy due to cooling technology change ($/MWH), α is capital recovery factor, θ is wet cooling technology water use (gal/MWH), K_{dry} is dry cooling technology capital cost ($/MW), K_{wet} is wet cooling technology capital cost ($/MW), OM_{dry} is dry cooling technology O&M cost ($), and OM_{wet} is wet cooling technology O&M cost ($).

The US Department of Energy through its National Energy Technology Laboratory has conducted extensive research over the years in the performance and cost of different cooling technology options. Data from their website was used to derive the economic value of cooling water. Table 3.1 shows cost comparison undertaken by the US Department of Energy for wet versus dry cooling water system for a reference 500MW coal-fired power plant. The data was used to estimate thermal power cooling water economic benefits.

Table 3.1: Wet versus Dry Cooling Water System for 500 MW Coal-fired Plant

	Wet Cooling	Dry Cooling
Capital Cost (US$ Mill)	38.8	83.8
Annual O&M Cost (US$ Mill)	2.284	4.124
Levelised annual cost (US$ Mill/yr)	7.332	15.022
Cost of Energy (mills/kWh)	2.09	4.29
Dry Cooling Incremental Cost of Energy (mills/kWh)	2.19	

(Source: National Energy Technology Laboratory, US Department of Energy)

3.2.3.3 Model Application – ACF Basin

3.2.3.3.1 Thermal Energy

Of the total surface water withdrawals in the basin, about 60% are used for cooling purposes in thermoelectric power generation. Although significant amounts of water are withdrawn, only a very small percentage (about 1% to 5%) is consumed and the rest is returned to the river. Table 3.2 gives specific information about the major thermal plants in the ACF basin.

Table 3.2: Thermal Power Generation Plants in the ACF Basin

Facility	Location	Capacity (MW)	Source of Water	24 hr Max withdrawal (MGD)	Monthly Average withdrawal (MGD)
Plant Atkinson (GPC) – **(retired 31 Dec 2002)**	Cobb, Ga		Chattahoochee	432	432
Plant McDonough (Georgia Power)	Cobb, Ga	517 MW	Chattahoochee	394	394
Plant Yates (Georgia Power)	Coweta, Ga	1295 MW	Chattahoochee	720	700
Plant Wansley (Georgia Power)	Heard, Ga	3939 MW	Chattahoochee	149.1	125.4
Farley Nuclear Plant (SNC)	Houston, Al	1711 MW	Chattahoochee	140	140
Plant Scholtz (Gulf Power Co.)	Jackson, Fl	98 MW	Apalachicola	108	108

(Source: USGS, 2007; www.georgiapower.com; and ww.eia.gov/cfapps/state/)

Cooling water withdrawal amounts vary from plant to plant and depend on the capacity of the plant and the wet cooling technology in use. For example Plant Yates withdraws the largest amount of water despite its low capacity, because its cooling system is predominantly based on the once-through cooling technology. This technology is based on the open-loop cooling cycle where the cooling water is drawn from the river, passed through the condenser, and released back into the river without recycling. On the contrary, Plant Wansley withdraws less water than Yates despite its significantly higher capacity because its cooling system is based on the closed-loop cooling technology. Water withdrawn from the river is passed through the condenser and then recycled through cooling towers where it cools by evaporation and returns to the condenser again. Despite the significant evaporative losses, the closed loop cooling technology is a far more efficient cooling technology, in terms of water use, than the open-loop cooling technology and has been adopted by most thermal plants in the basin. Figure 3.12 shows the cooling water use efficiencies for different thermal plants. The figure shows that besides cooling technology, the capacity of the plant impacts its cooling water use efficiency, with the smaller plants being less efficient than the large ones due to economies of scale.

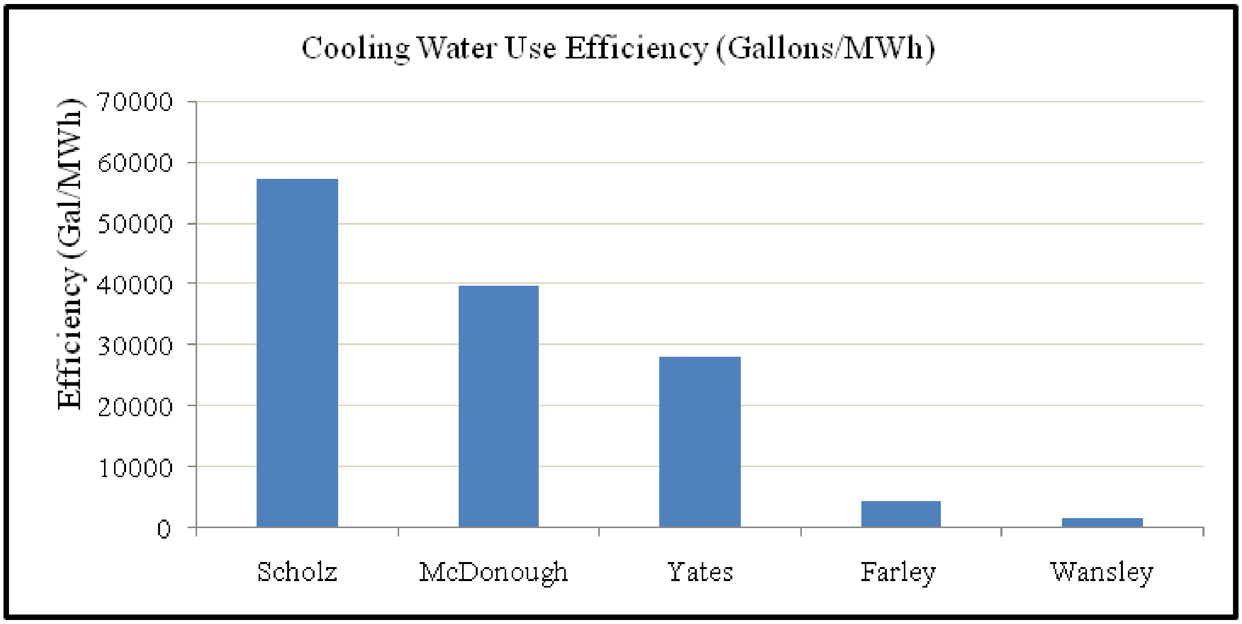


Figure 3.12: Thermal Power Generation Cooling Water Use Efficiency

Figure 3.13 shows the relationship between cooling water value and the cooling water use efficiency for the five plants. The value of cooling water decreases with the efficiency of water use. The average value for the basin is $130/acre-foot and varies between $12/acre-foot to $ 429/acre-foot depending on water availability and water use efficiency.

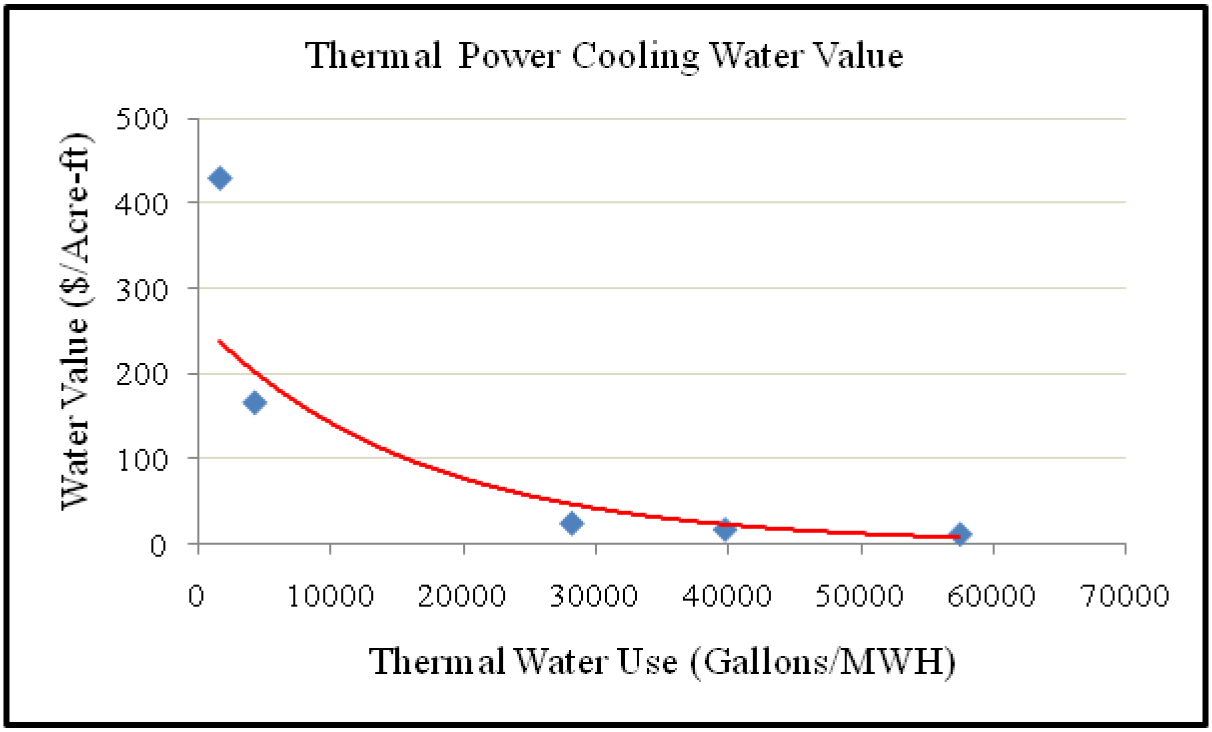


Figure 3.13: Thermal Power Generation Cooling Water Value

3.2.4 Valuation of Recreation Water Use

The approach used to determine recreation water use benefits is based on consumer willingness to pay for recreational opportunities available at a given recreation site. Recreation benefits accrue from both boating and non-boating water use. The specific information required for estimation of regional recreation benefits include: number of visits, spending per visitor, and capture rate. This approach is similar to that used by the US Corps of Engineers for estimation of economic benefits of recreation water uses at all their recreation sites around the country (USACE, 1998 and 2003). The economic benefits are computed from the relationship:

Economic benefits = (total recreation visitor expenditure) x (capture rate)

3.2.4.1 Estimation of Recreation Visitor Expenditure

Total recreation visitor expenditure is obtained by multiplying average expenditure per person trip by the number of person trips for each visitor category and then summing the results across all categories. The visitors are classified as boaters and non-boaters. Historical data on visitation rates to different USACE recreation facilities (including the four reservoirs in the ACF basin) is stored in the USACE Natural Resource Management System (NRMS) database and contains estimates of the number of visitors for each category in person trips (visits). The data has also been converted into party days using average lengths of stay and party sizes for each category of visitors (Propst et al., 1996). The average expenditure per visit is estimated from visitor expenditure surveys conducted periodically at individual recreation sites. The NRMS database contains site specific information on all the revenues and fees collected each year. This information, together with information collected from visitor expenditure surveys, is used to derive the visitor expenditure profiles for each recreation site. USACE has developed representative visitor spending profiles for all their recreation sites. These were developed from survey data collected during 1989 and 1990 (Propst et al., 1992). The spending profiles were recently updated through another USACE visitor expenditure survey (Chang et al., 2003). The survey sampled visitors from 16 CoE recreation sites and elisted information on the amounts they spent for goods and services during their recreation trips to the sites. Survey results highlight differences in spending patterns across visitor groups depending on the specific activities the visitors are involved in at the recreation site and on the duration of their visit. For example, trip spending within 30 miles of the recreation site varied from $12 for day use non-boaters to $84 for overnight boaters. Table 3.3 shows the average spending profiles at CoE recreation sites.

Table 3.3: Average visitor spending profiles ($ per person trip).

Mean Values	Camper (Boater)	Camper (non-Boater)	Day user (Boater)	Day user (non-Boater)	Other overnight (Boater)	Other overnight (non-Boater)
Total trip spending US$	84.88	85.84	25.07	15.08	107.34	82.12
Party Size	3.53	2.76	2.78	2.77	3.27	2.47
Total Nights	4.62	5.20	0	0	2.9	6.24

(Source: CoE, 2003)

3.2.4.2 Estimation of Capture Rate

The capture rate is the proportion of total visitor spending that is retained in a region's economy (i.e., the part that does not escape because of leakages to sectors outside the region). It represents the portion of visitor spending reflected in the local economy through direct sales effects.

3.2.4.3 Computation of Recreation Water Use Benefits

Annual recreation benefits are estimated using visitation data and price inflated expenditure data (using the 2003 USACE average visitor expenditure profiles) and applying the USACE recommended local capture rates (assumed not to vary much from year to year). Capture rates have been developed by USACE for all their recreation sites

(Propst et al., 1998; and Wang et al., 2003). Table 3.4 shows capture rates for major USACE recreation sites in the ACF basin.

Table 3.4: Capture Rates for major Recreation sites in the ACF Basin

Site	Capture Rate (%)
Seminole	62
Lanier	67
George WF	59
West Point	64

(Source: USACE, 2003)

3.2.4.3.1 Boater Recreation Visitor Projections

Seasonal visitation – lake level functions are used to forecast boater visitation rates corresponding to different lake levels. The functions are derived from observed historical recreation data for the major recreation sites in the basin. Figure 3.14 shows the boater visitation function for Lake Lanier. The figure shows that visitation numbers increase with rising lake levels until some threshold (flood pool level) when they level off. The figure also shows differences in visitation rates during different seasons of the year with the highest rates being observed during the summer season and the lowest during winter. Table 3.5 shows Lake Lanier seasonal visitation – lake level functions for boaters. These functions form the basis for projecting future visitation rates at the recreation sites. Future visitation projections are based on lake level sequences generated by the water resources assessment model under different scenarios.

3.2.4.3.2 Non-boater Recreation Visitor Projections

There is no distinct relationship between non-boater visitation rates and lake levels (Figure 3.15). Instead a uniform average annual growth rate of 0.7% is applied in forecasting the seasonal non-boater rates during the assessment period. This rate was derived from historical data on non-boater visitation to the recreation sites.

Table 3.5: Lake Lanier Boater Visitor-Water Level Functions

Function	**Visitation = aH^2+bH+c**			H=Lake level (ft)
	a	b	c	R^2
Spring	348.35	-7.25×10^5	4.0×10^8	0.985
Summer	444.71	-9.2×10^5	5.0×10^8	0.945
Fall	142.21	-2.94×10^5	2.0×10^8	0.951
Winter	178.14	-3.71×10^5	2.0×10^8	0.991

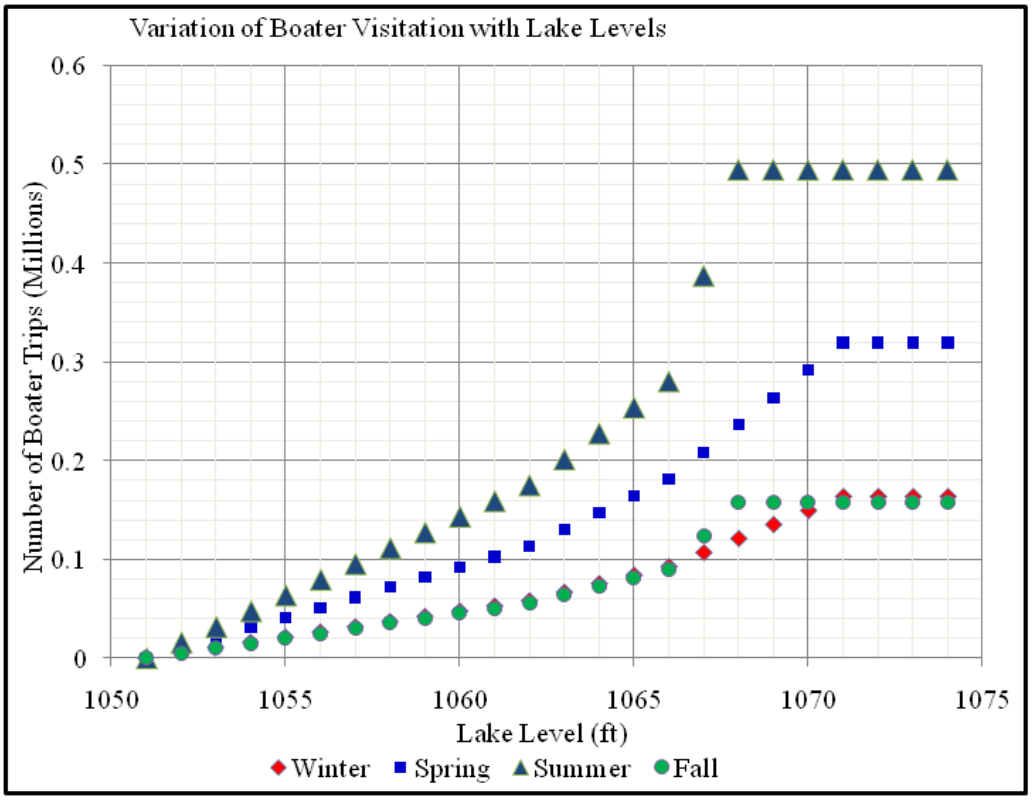


Figure 3.14: Lake Lanier Boater Visitation-Water Level Functions

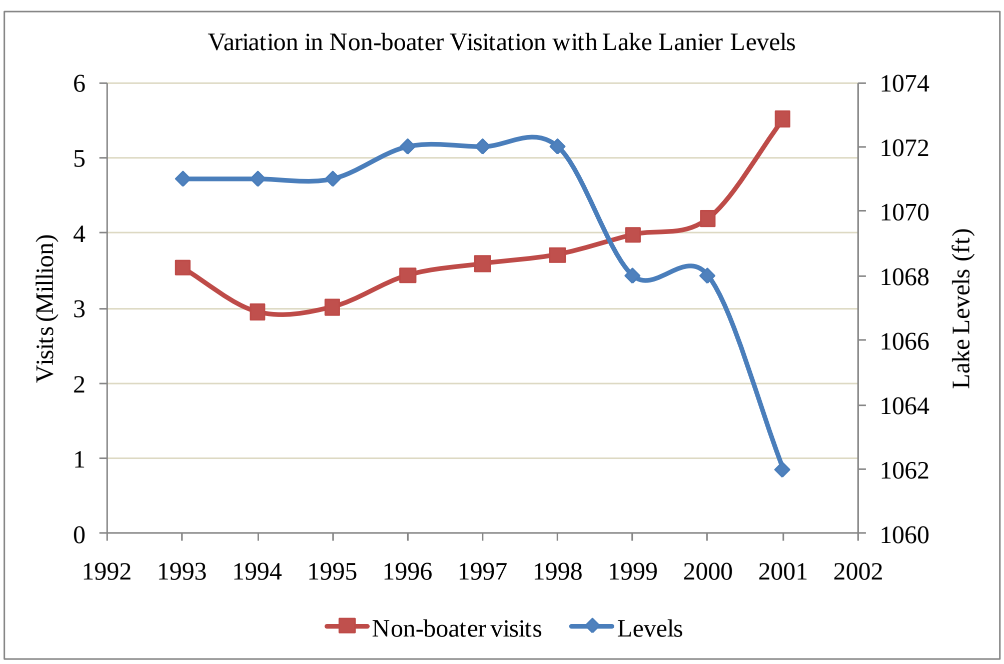


Figure 3.15: Lake Lanier Non-Boater Visitation Trend

In a study for the Atlanta Regional Commission (ARC, 2004), surveys of actual expenditures by local and out-of-town recreation visitors to Lake Lanier were used to estimate recreation water use benefits for the lake. Based on the 2004 visitation rates and expenditures, the study estimated the local recreation benefits for Lake Lanier to be US$ 278 million.

3.2.5 Valuation of Environmental Water Use

Maintenance of adequate water supplies for environmental conservation and sustainability of aquatic life is one of the most important water use requirements in the ACF basin. The basin provides habitat for 65 species listed as endangered or threatened under the Endangered Species Act, including four freshwater mussels and the gulf sturgeon (USFWS, 2009b). The preservation of healthy ecosystems provides many benefits to the basin riparians including abundant fisheries, wildlife habitat, recreation, and clean water. Particularly, the basin sustains a very unique ecosystem and rich fishing industry in the Apalachicola Bay.

This research did not undertake comprehensive valuation of environmental water use due to data constraints. However, environmental water requirements assumed to be met through specified minimum flow requirements at different critical sections in the basin. By varying minimum flow requirements, water use benefits foregone by upstream water users were estimated and used to provide the opportunity cost of environmental water use. This approach is commonly used especially when it is difficult or controversial to value environmental services (Medellín- Azuara et al., 2006).

CHAPTER 4: CLIMATE CHANGE IMPACT ASSESSMENTS

4.1 Introduction

The discussion in this chapter focuses on assessment and quantification of potential climate change impacts on the spatial and temporal availability of water resources in the ACF basin. Downscaled sequences of precipitation and temperature data from GCMs are used as inputs to hydrologic models to simulate the hydrologic response of the basin under potential future climate scenarios. The watershed runoff sequences generated are used to drive the water resources assessment models discussed in Chapter 3 to generate sequences of physical outputs including weekly energy generation, reservoir levels and discharges, and consumptive water demands at all system nodes. The sequences of physical outputs are used as inputs to the economic assessment models to estimate potential economic impacts associated with future climate change.

Projecting regional impacts of climatic change and variability relies first on General Circulation Models (GCMs), which develop large-scale scenarios of changing climate parameters, associated with different concentrations of greenhouse gases in the atmosphere. This information is typically at too coarse a scale to make accurate regional assessments. As a result, more effort has recently been put into reducing the scale and increasing the resolution of climate models through various techniques such as downscaling or integrating regional models into the global models. It should be emphasized that these model results are not intended as specific predictions, but rather are scenarios based on the potential climatic variability and change driven by both natural variability and human-induced changes. Nonetheless, they are useful for assessing potential future conditions.

The climate change impact assessments undertaken follow five basic steps:
(a) Identification of appropriate emission scenarios and GCM data;
(b) Bias correction and downscaling GCM data to appropriate regional/local scale;
(c) Generation of consistent climate forcing (rainfall/temperature) sequences;
(d) Generation of hydrologic scenarios (soil moisture, evapotranspiration, and runoff) for all basin watersheds using the downscaled sequences of temperature and precipitation;
(e) Assessment of water resources system response to future hydrologic scenarios.

4.2 Global scale Climate Projections

The Intergovernmental Panel on Climate Change (IPCC) has generated a wealth of technical information and reference material related to the science of climate change. As part of this effort, the IPCC released a Special Report on Emissions Scenarios (SRES) that groups future greenhouse gas emission scenarios into four separate categories that depend upon future potential developments in demography, economic development, and technological change (Nakicenovic and Swart 2000). Together they describe divergent potential futures that encompass a significant portion of the underlying uncertainties in the main driving force behind global climate change. The IPCC has also collected and archived experimental results associated with these scenarios for several commonly used Global Circulation Models (GCMs). While GCMs are at present the most powerful and widely used means for exploring potential future climates, they differ in their representation of the climate sensitivity to changes in atmospheric greenhouse gas composition. Moreover, the inter-model differences in projected regional climate changes are much larger than the global scale differences even when models are forced with a common emission scenario.

4.3 Generation of Consistent Regional Climate Forcing

Despite the recent advances in global climate modeling, existing GCMs are still not regarded as sufficiently detailed for direct application in regional climate studies. It is therefore often necessary to represent the regional climate response in greater spatial detail than is resolved by the coarse resolution GCMs. The simplest approach to representing such detail is to uniformly apply changes at large GCM nodes across finer scale observed data. This can be achieved in a number of ways, including applying the changes from the node nearest the study region or by interpolating changes from a number of nearby GCM nodes. However, due to large regional uncertainties, using a single node as the basis for impact assessment is not recommended (IPCC, 1999). Furthermore, depending on the region and variables involved, it may not be a reasonable assumption that small scale responses occur uniformly. A wide range of downscaling techniques have been developed and applied in past studies. They range from simple regression models to complex statistical techniques.

The regional scale precipitation and temperature sequences used in this research are based on previous work on climate change assessment for the ACF basin (GWRI, 2010, Zhang and Georgakakos, 2011). In generating these sequences, temperature and precipitation outputs from 13commonly used GCMs (Table 4.1) are used to estimate future climate conditions under two emission scenarios, A1B and A2, corresponding to the IPCC's medium and high emission projections.

The Joint Variable Spatial Downscaling (JVSD) method was used to produce high resolution gridded hydrological datasets suitable for regional watershed modeling and assessments for the ACF basin. JVSD is implemented as a two step process: bias correction and spatial downscaling (Figure 4.1). The approach first adjusts output from the GCMs to account for tendencies in the model to be too wet, dry, warm, or cool during the historical period (bias correction), and then the adjusted data are converted to regional data (spatial downscaling).The JVSD spatial downscaling component is based on matching the bias-corrected temperature and precipitation patterns with similar observed patterns (historical analogues) over the assessment region (e.g., the ACF river basin). The JVSD approach was applied to output from all 13 GCM simulations under two emission scenarios, resulting in 26 regional - scale climate change data sets. A short form nomenclature is used to make reference to each of the climate scenarios in subsequent chapters (Table 4.1). For example S1A stands for “BCCR-BCM2.0, Norway” under A1B emission scenario while S1B stands for “BCCR-BCM2.0, Norway” under A2 emission scenario.

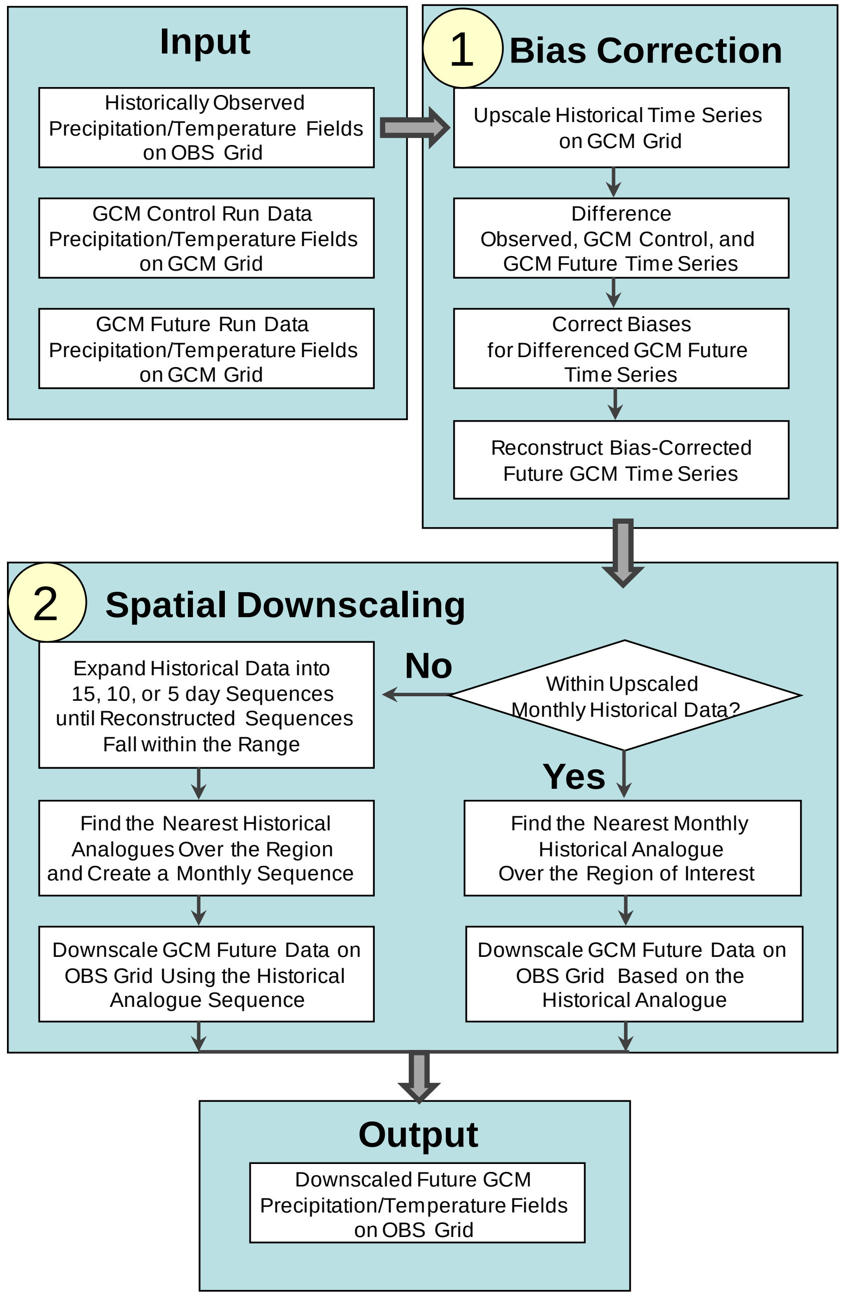


Figure 4.1: Joint Variable Spatial Downscaling Method (Source: GWRI, 2010)

Table 4.1: Global Circulation Models Used

Model	**Contributor**	**Short form notation**
BCCR-BCM2.0, Norway	Bjerknes Centre for Climate Research	S1
CGCM3.1(T63), Canada	Canadian Centre for Climate Modeling and Analysis	S2
CNRM-CM3, France	Centre National de Recherches Meteorologiques	S3
CSIRO-Mk3.5, Australia	CSIRO, Australia	S4
ECHAM5/MPI-OM, Germany	Max Planck Institute for Meteorology	S5
GFDL-CM2.1, USA	Geophysical Fluid Dynamics Laboratory, NOAA	S6
GISS-AOM, USA	NASA Goddard Institute for Space Studies	S7
MIROC3.2(hires), Japan	CCSR/NIES/FRCGC, Japan	S8
CCSM3, USA	National Center for Atmospheric Research (NCAR),	S9
PCM, USA	NCAR, NSF, DOE, NASA, NOAA	S10
UKMO-HadCM3, UK	Hadley Centre for Climate Prediction and Research	S11
MIUB ECHO-G, Germany/Korea	Meteorological Institute of the University of Bonn	S12
INM-CM3.0, Russia	Institute for Numerical Mathematics	S13

Source: GWRI, 2010.

4.4 Simulation of Hydrological Changes

The resulting temperature sequences for each ACF watershed were converted into potential evapotranspiration demand using the Hammon PET method and are used together with the associated precipitation sequences as the basis for the hydrological assessments. These sequences are expressed in the form of frequency curves for the historical (1900-1999) and future time series (2000-2099) (Figures 4.2 (a) and (b) for an example for the Buford watershed) from which the following conclusions can be drawn:

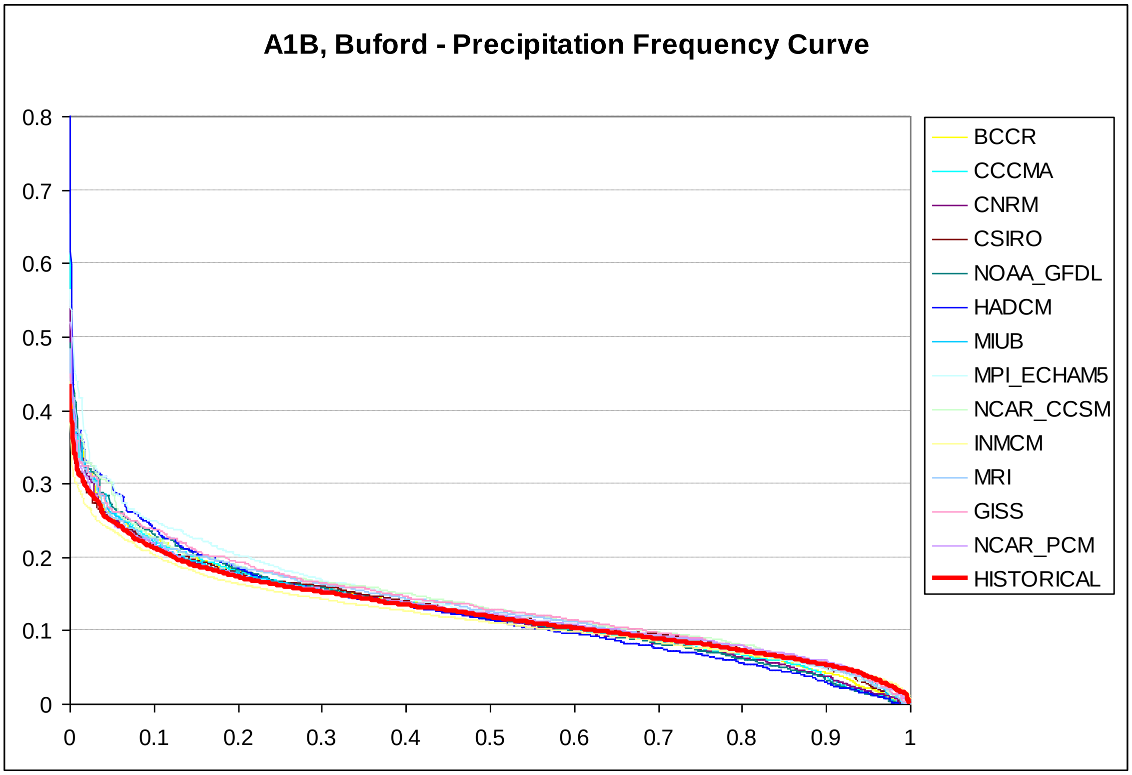
(1) Both A1B and A2 scenarios exhibit increasing average PET for all ACF watersheds. Such increases intensify for watersheds in lower latitudes.

(2) PET increases are uneven across the frequency distribution, with high PET values experiencing considerably higher increases than the average or low PET values.

(3) Average precipitation changes over the ACF basin are insignificant. However, both distribution tails show significant changes, with high precipitation values exhibiting significant increases and low precipitation values exhibiting significant decreases. Namely, while the precipitation mean appears to stay comparable to the historical level, both extremes (floods and droughts) are expected to intensify; Combining this and previous findings, most ACF watersheds are likely to experience wetter winters (especially the watersheds in the upper Chattahoochee—Buford and West Point) and hotter summers (especially the watersheds in the Flint River—Montezuma and Albany) with more extreme floods and droughts possible;

(4) The A2 scenarios changes are more significant than those of A1B; and

(5) The differences among the GCM scenarios indicate large uncertainties associated with long-range climate simulations. It is thus important that hydrologic and water resources assessments be carried out for multiple scenarios and the results interpreted from an ensemble perspective. Such assessments are taken up in the following chapters.



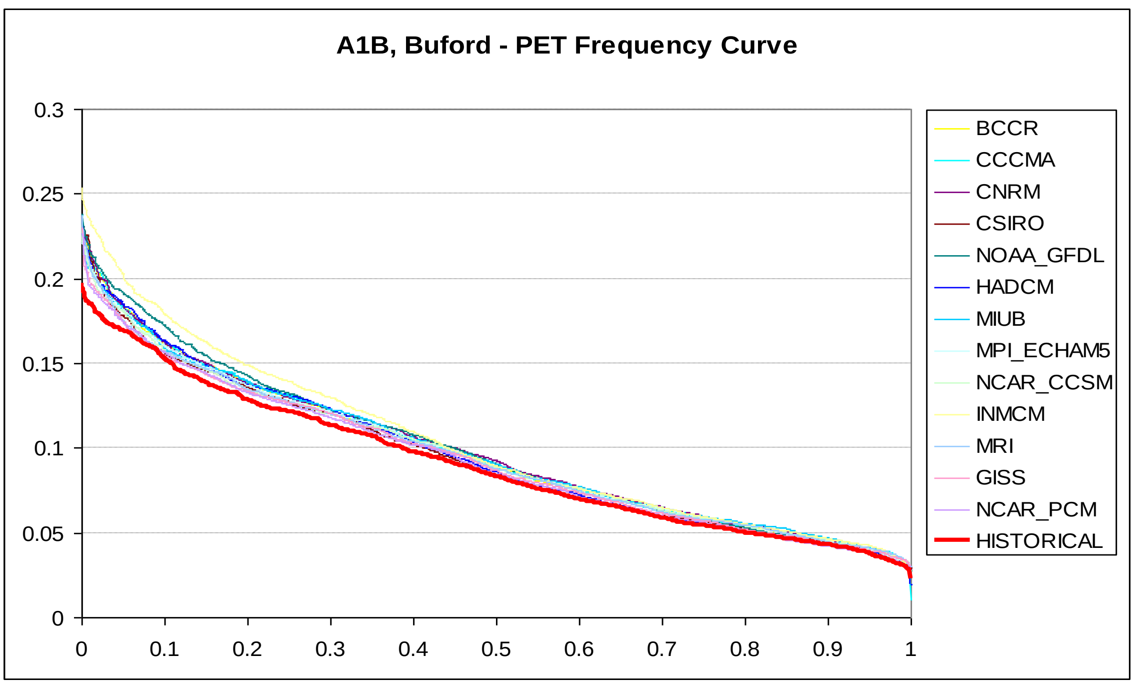
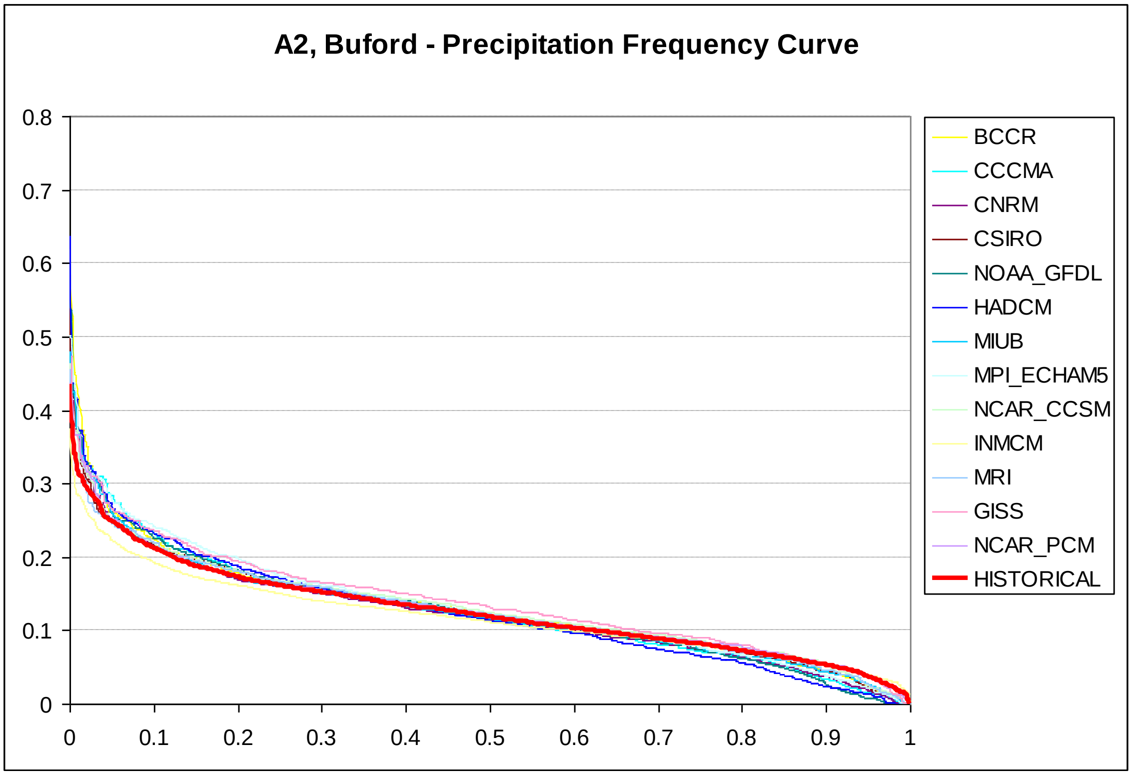


Figure 4.2 (a): Frequency Curves of Precipitation and PET Sequences for A1B Scenarios



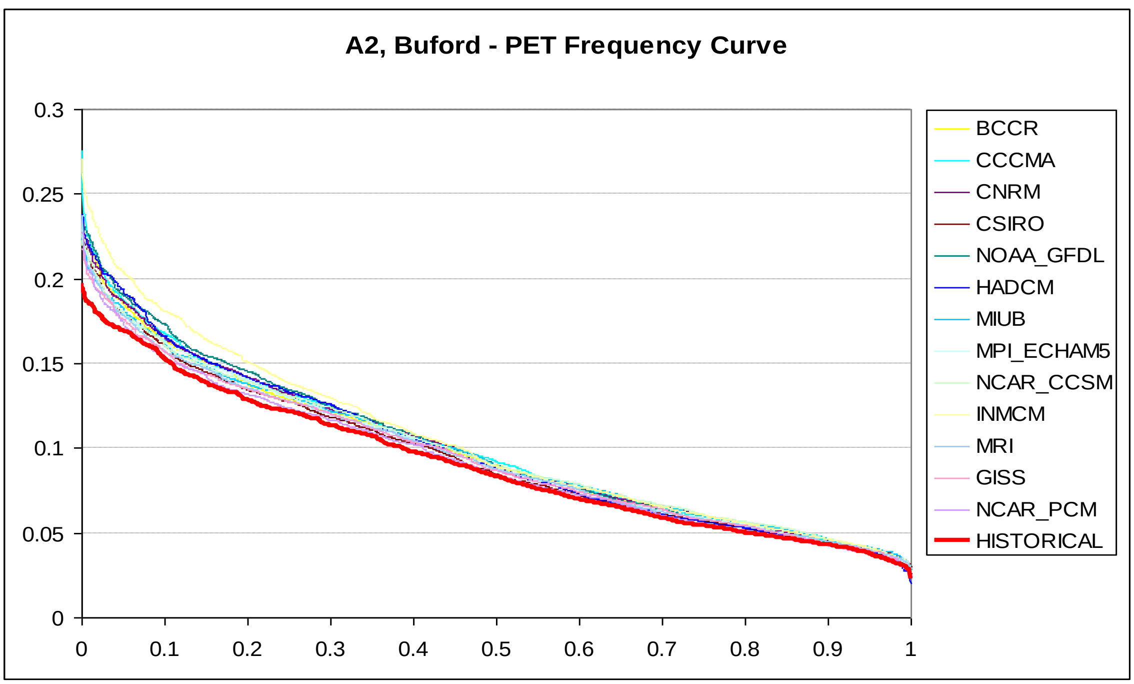


Figure 4.2 (b): Frequency Curves of Precipitation and PET Sequences for A2 scenarios

CHAPTER 5: BASELINE HYDRO-ECONOMIC ASSESSMENTS

The methodologies discussed in Chapter 3 are applied to the ACF basin to simulate the physical and economic performance of the system under baseline conditions of current water resources management objectives, minimum environmental flow requirements, existing reservoir operation policy, and other system purposes. The assessments are driven by projected water demand growth and potential climate change scenarios and are only referred to as "baseline" with respect to current water resources management objectives and policies. Assessment of alternative management objectives and policies is the subject of the next chapter.

5.1 Simulation of System Performance

The scenario assessment model of the ACF-DSS is used to evaluate the system performance under historical and potential future climate change hydrological conditions, current and projected water demand, and the Corps of Engineers Revised Interim operating policy (RIOP). System nodes are defined representing major water storage and hydropower generation facilities, water supply and demand points, and points at which specific flow constraints are imposed in the basin. Figure 5.1 shows a schematic representation of the major system nodes of the ACF basin. Watershed runoff sequences generated from potential future climate change scenarios are used to drive the model which simulates weekly operation of the ACF system under the prescribed conditions. Model input data includes: water demand targets at different nodes; net basin supplies; reservoir release rules; reservoir storage and release limits; head loss functions; power load components; hydro-turbine characteristics; tail-water curves; hourly power demand sequence; and in-stream flow constraints.

At the beginning of each week of the simulation horizon, the model generates inflow forecasts; sets the water supply, energy generation, and minimum flow requirements; activates the long range optimization model to determine the most appropriate reservoir releases; simulates the response of the system for the upcoming week; and repeats this process at the beginning of the following week. At the completion of the forecast−decision−simulation process, the model generates sequences of all system performance measures including consumptive water demands at all nodes, weekly energy generation sequences at all generation facilities, reservoir levels, and inflow and release sequences for all storage facilities in the system. These sequences are used to quantify the physical outputs of the system under the prescribed conditions over the entire assessment horizon. The sequences of physical outputs also used as inputs for the economic assessment models that generate system economic performance measures.
Discussion of some of the important system performance measures follows.

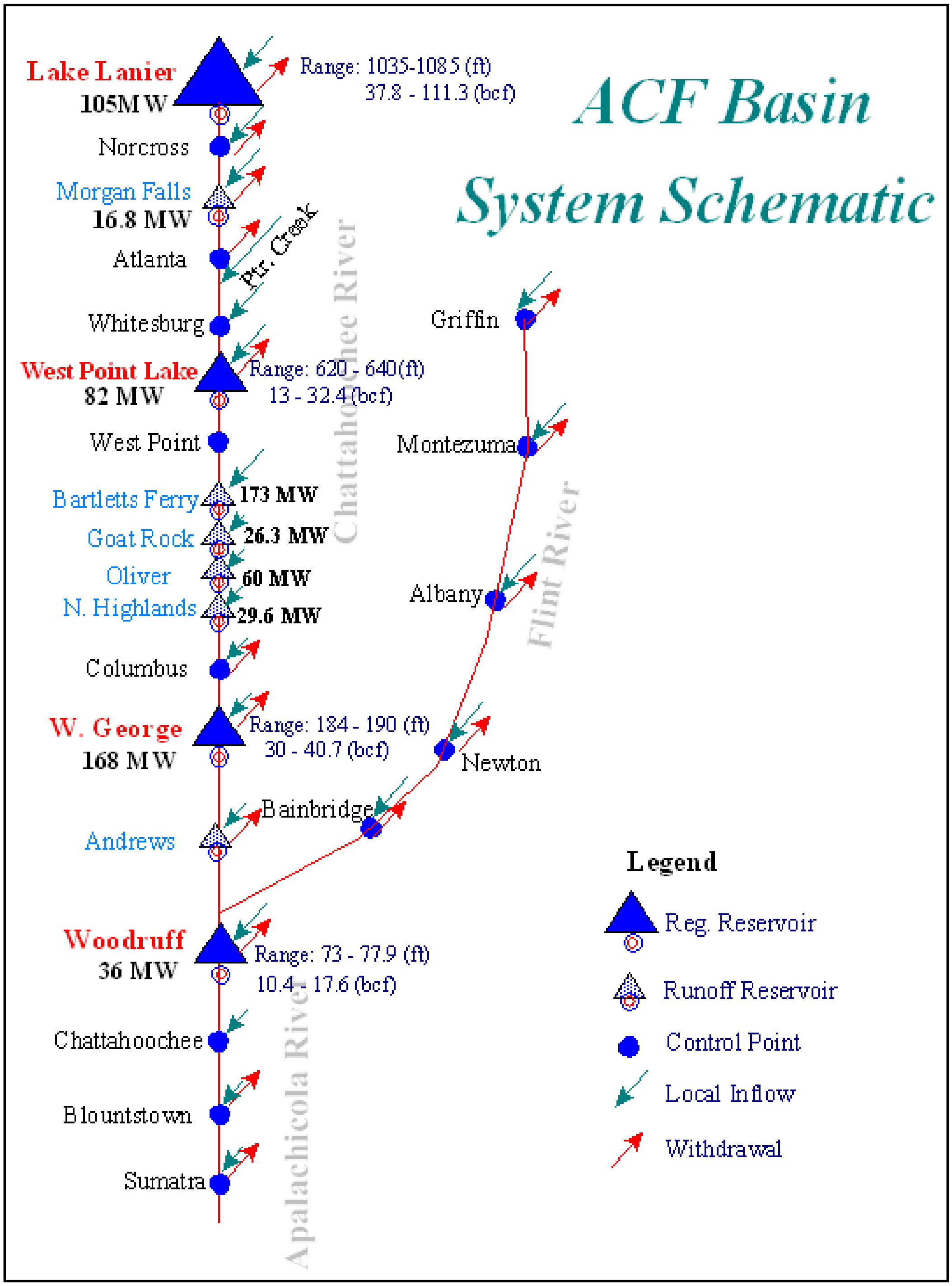


Figure 5.1: Schematic of the ACF System (Source: GWRI, 2009)

5.1.1 Physical System Performance Measures

5.1.1.1 Water Supply Deficits

Based on the water demand projections discussed above, the water resources assessment model (ACF DSS) was used to simulate annual water withdrawals and deficits at all system nodes subject to specified management objectives, environmental flow requirements, and other important system constraints. Figure 5.2 shows the basin-wide annual water supply deficits for the entire assessment period. The figure shows that water supply deficits occur for several climate change scenarios with varying frequency and severity. In the driest scenario, deficits range up to the full water supply target and occur over durations of up to 2 years. For most of the scenarios, however, violations occur for less than 0.5% of the time. During the earlier years of the assessment period (2000 – 2007), simulated deficits under all future climate change scenarios are less common and of a small magnitude (<50 cfs). However, in the later years the deficits increase in frequency and magnitude (up to 387 cfs). This can be attributed to a combination of factors including high water demands and increasing frequency and severity of drought events in the later years. More than 90% of the total deficit occurs in the upper Chattahoochee above the Peachtree gauge. This is attributed to the high municipal water demand for the Metropolitan Atlanta area. Despite a smaller percentage of total deficits occurring in the Flint sub-basin (<10%), it is important to note that the deficits are more frequent due to inadequate water storage infrastructure on the Flint River for low flow augmentation.

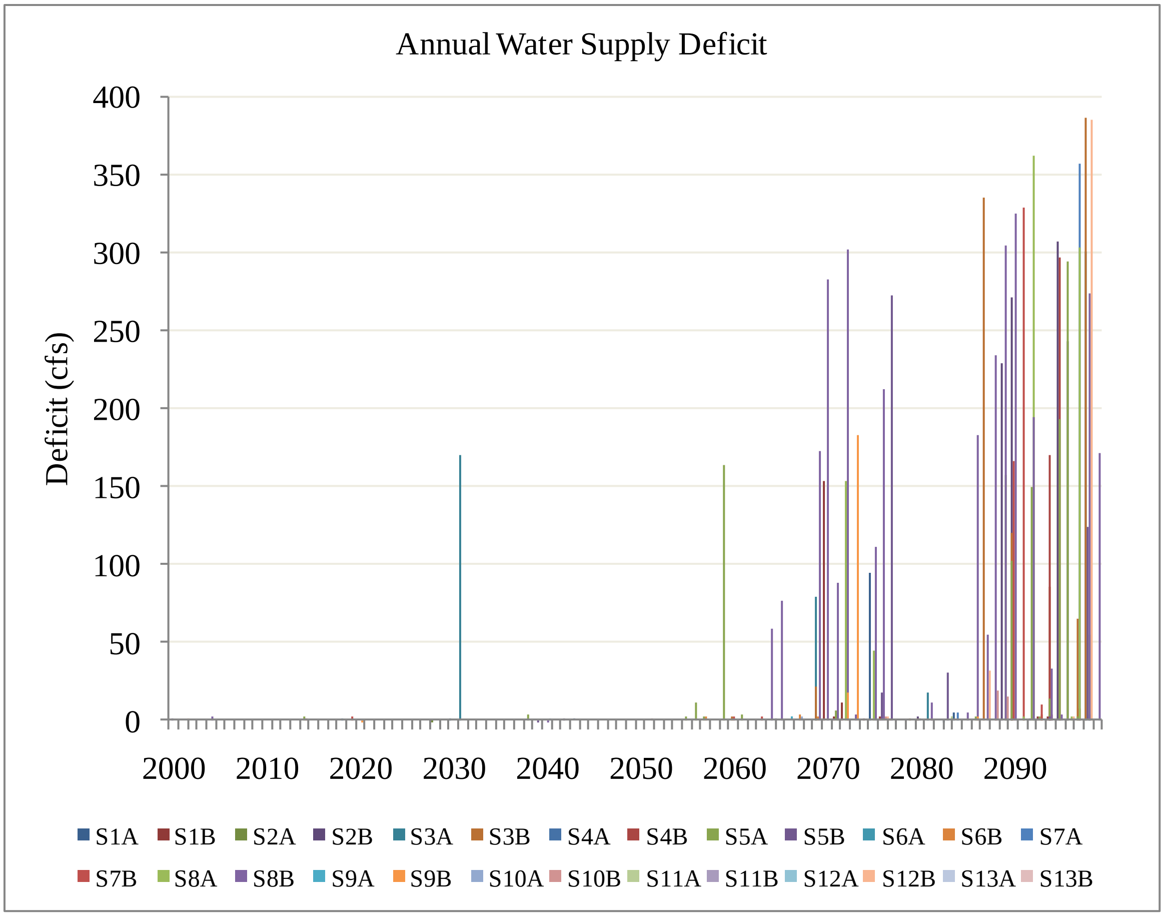


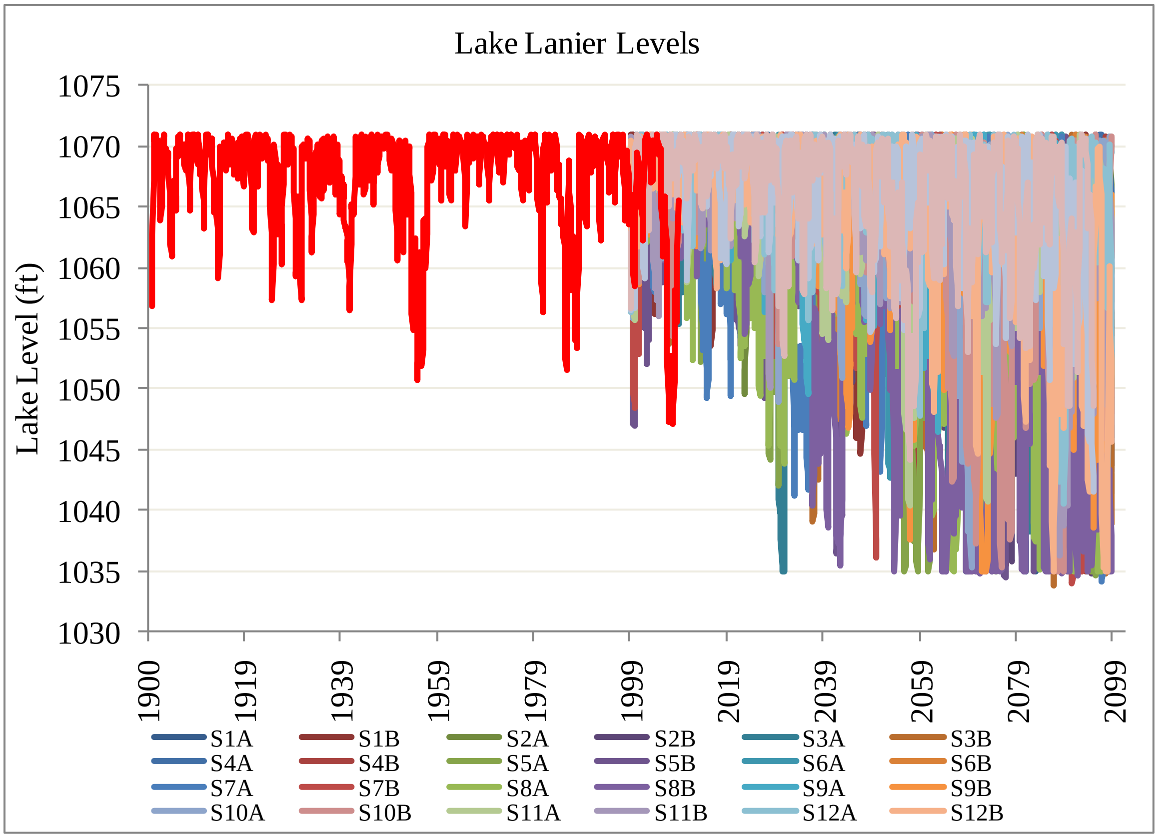
Figure 5.2: Baseline Annual Water Supply Deficit

5.1.1.2 Reservoir Levels Fluctuation

Figure 5.3 shows historical and future Lake Lanier levels and corresponding duration curves. Most of the future frequency curves fall below the historical frequency curve implying that the lake is most likely to experience lower water levels under potential future climate conditions compared to the historical conditions. Figure 5.4 shows the extent of reservoir depletion[3] for the four reservoirs under future climate scenarios. Lake Lanier experiences full depletion in a total of up to 13 months over the

[3] Reservoir depletion refers to reservoir drawdown into dead storage.

assessment period, depending on the climate scenario. The lake experiences depletion in 12 out of the 26 climate scenarios. The trend in water level fluctuation for the other three reservoirs is quite similar to that for Lake Lanier but with less frequent reservoir depletion over fewer climate scenarios (Figure 5.5). The potential for the four reservoirs to experience lower lake levels in future could pose serious water resources management challenges in the basin unless appropriate intervention measures are taken soon rather than later.



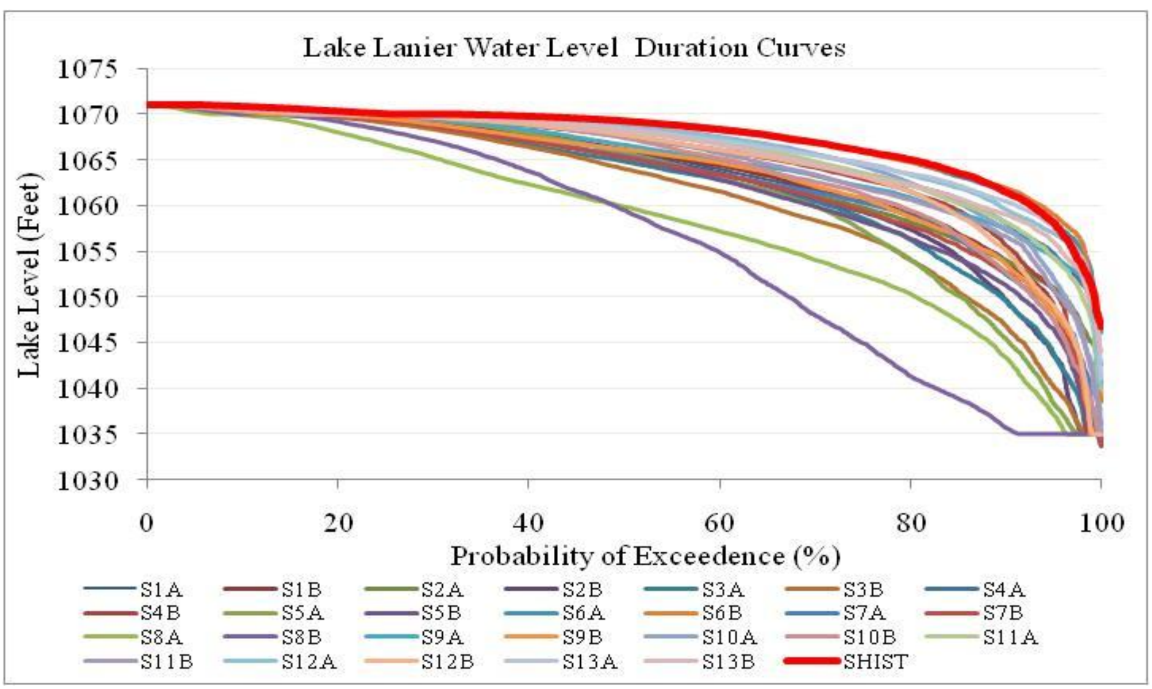


Figure 5.3: Lake Lanier Level Fluctuation under Baseline Scenario

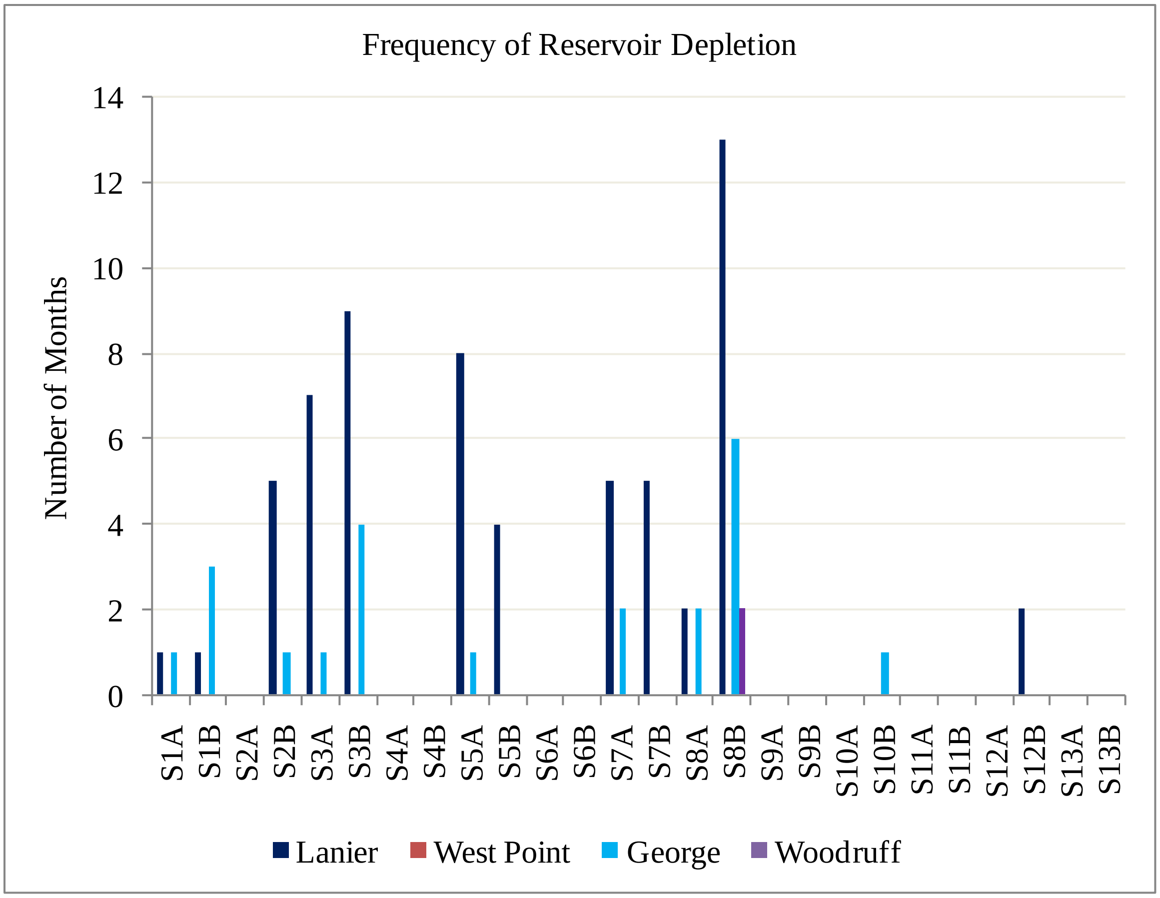


Figure 5.4: Potential Reservoir Depletion under Baseline Scenario

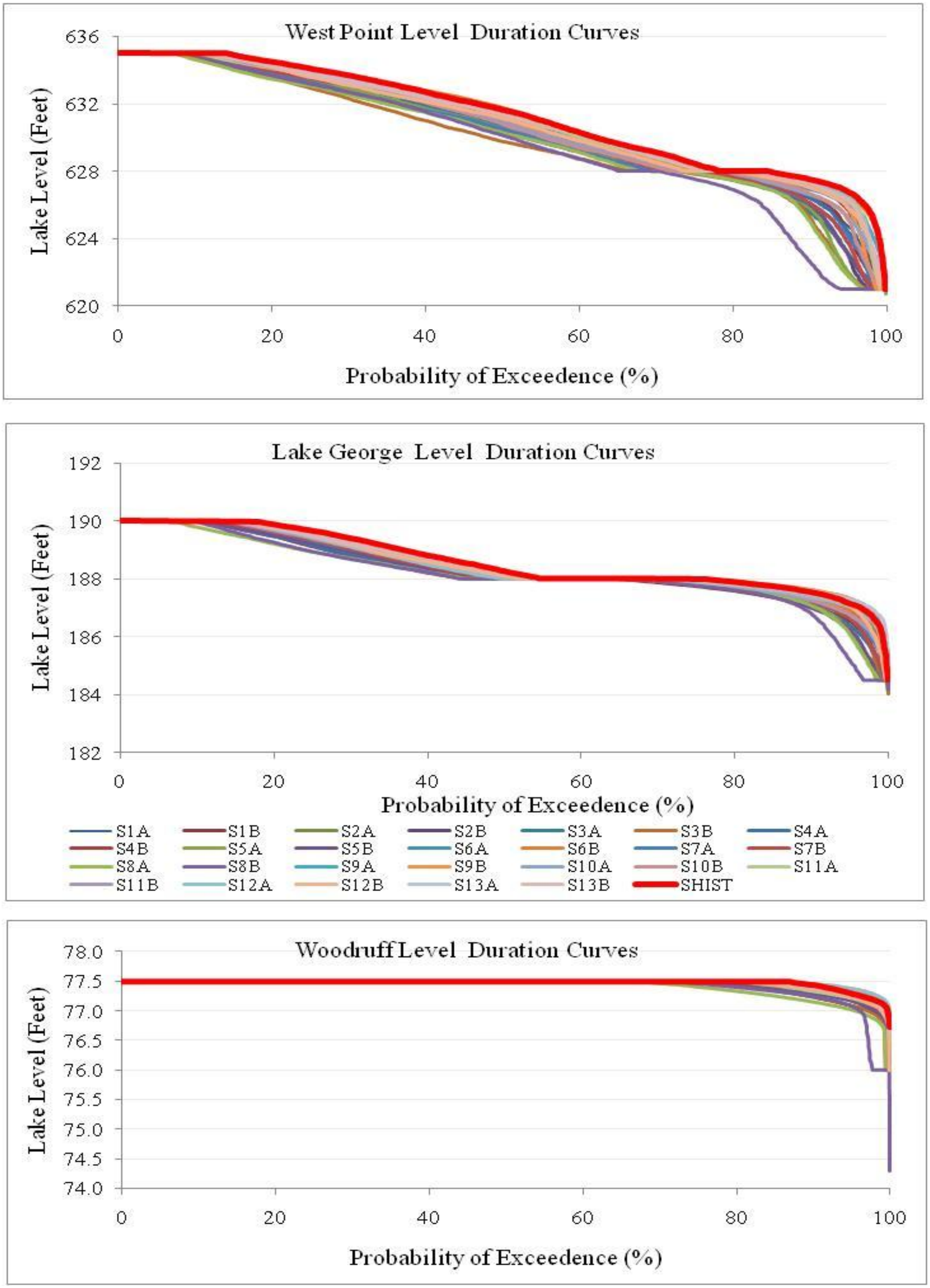
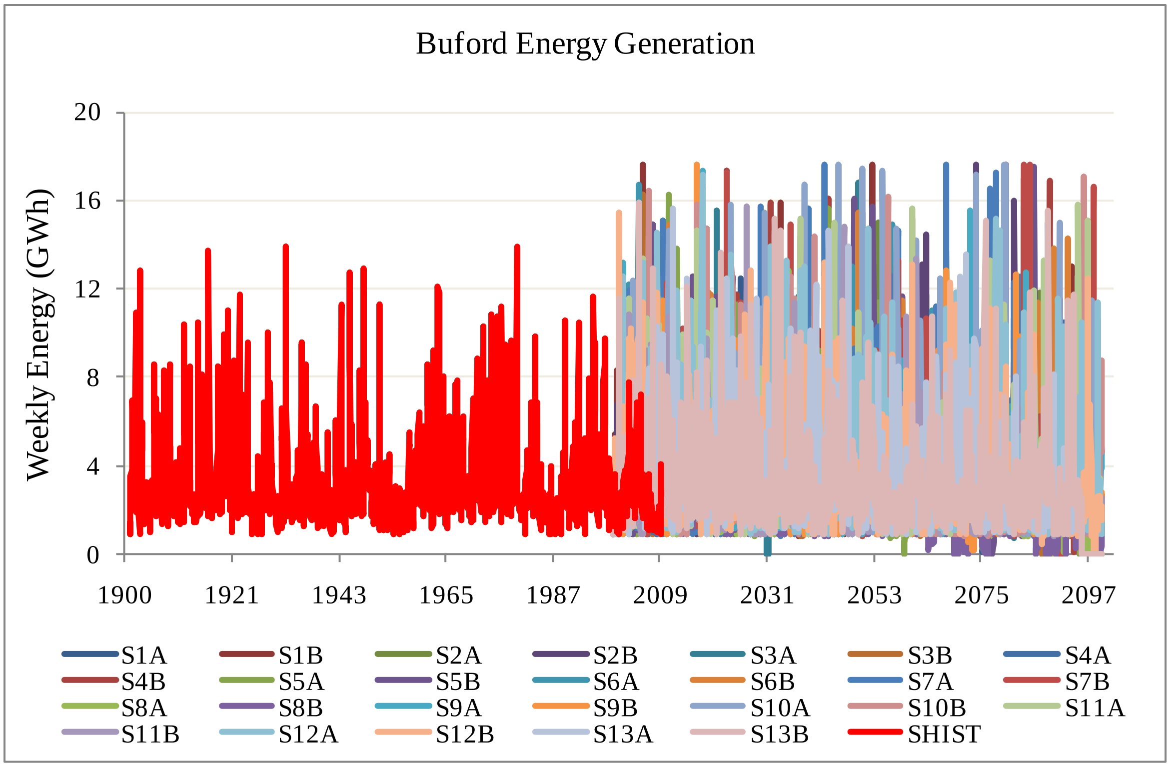


Figure 5.5: Level Duration Curves under Baseline Scenario (West Point, George and Woodruff)

5.1.1.3 Variability in Hydropower Generation

Figure 5.6 shows historical and future weekly hydropower generation at Buford and corresponding duration curves. About 70% of the energy generation frequency curves fall below the historical curve indicating a high likelihood of lower hydropower generation under future climate scenarios than the baseline in most years. The situation is expected to be worse under extreme drought conditions as all future frequency curves fall below the historical curve at the very low end of the distributions. Figure 5.7 shows potential incidences of generation failure at the four reservoirs under future climate scenarios. Buford experiences generation failure in a total of up to 8 months over the assessment period, depending on the climate scenario. Hydropower generation failure occurs in 12 out of the 26 climate scenarios. The trend in hydropower generation at George and West Point is quite similar to that of Buford but with less frequent generation failures over fewer climate scenarios (Figure 5.8). Woodruff's response is quite different from the other three in that future energy generation is less than the historical generation for most future climate scenarios and years. Generally, climate change impacts on hydropower generation in the basin are relatively mild due to the significant storage capacity in the system that tends to augment low flows in most future climate scenarios.



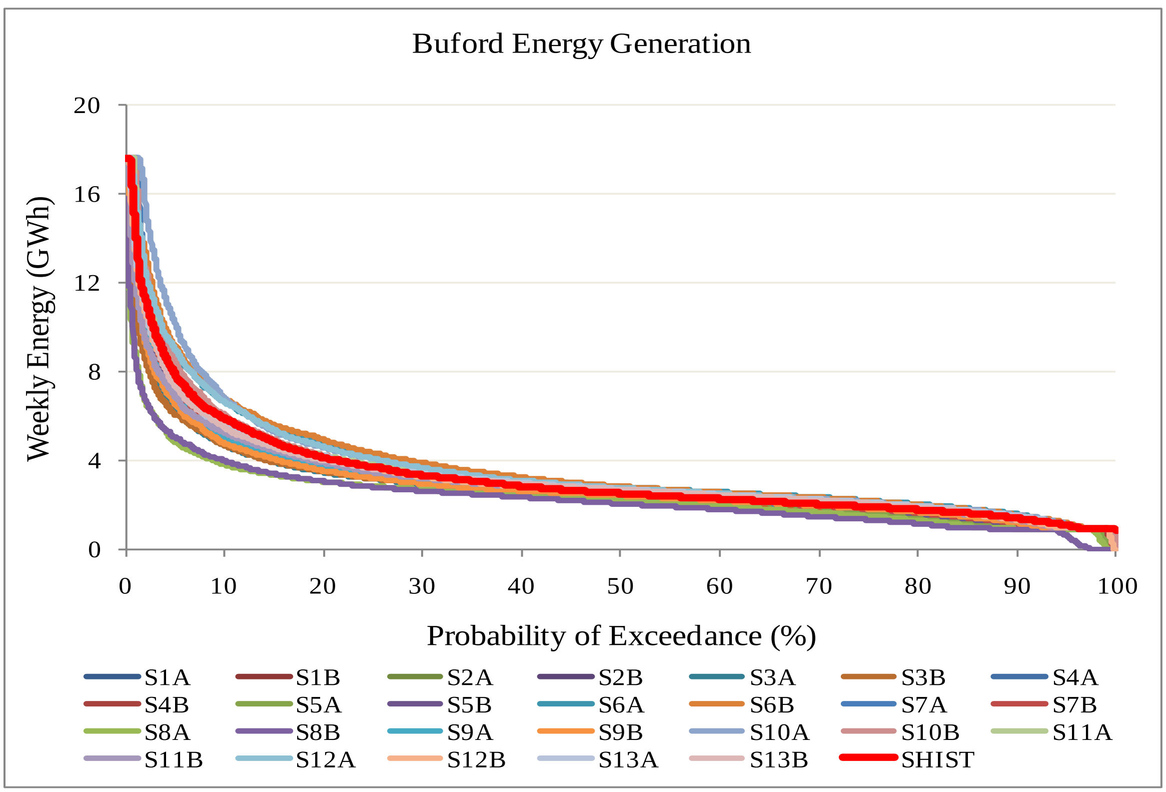


Figure 5.6: Buford Hydropower Generation under Baseline Scenario

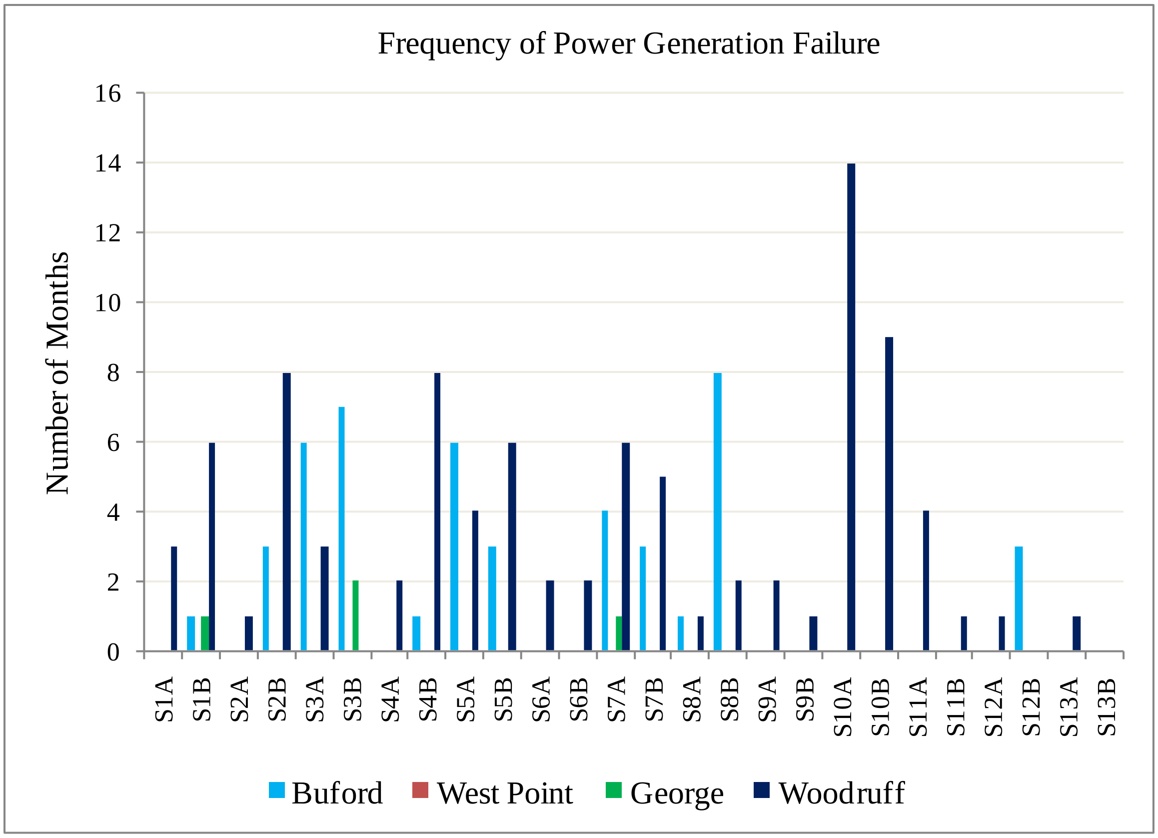


Figure 5.7: Potential Hydropower Generation Failure under Baseline Scenario

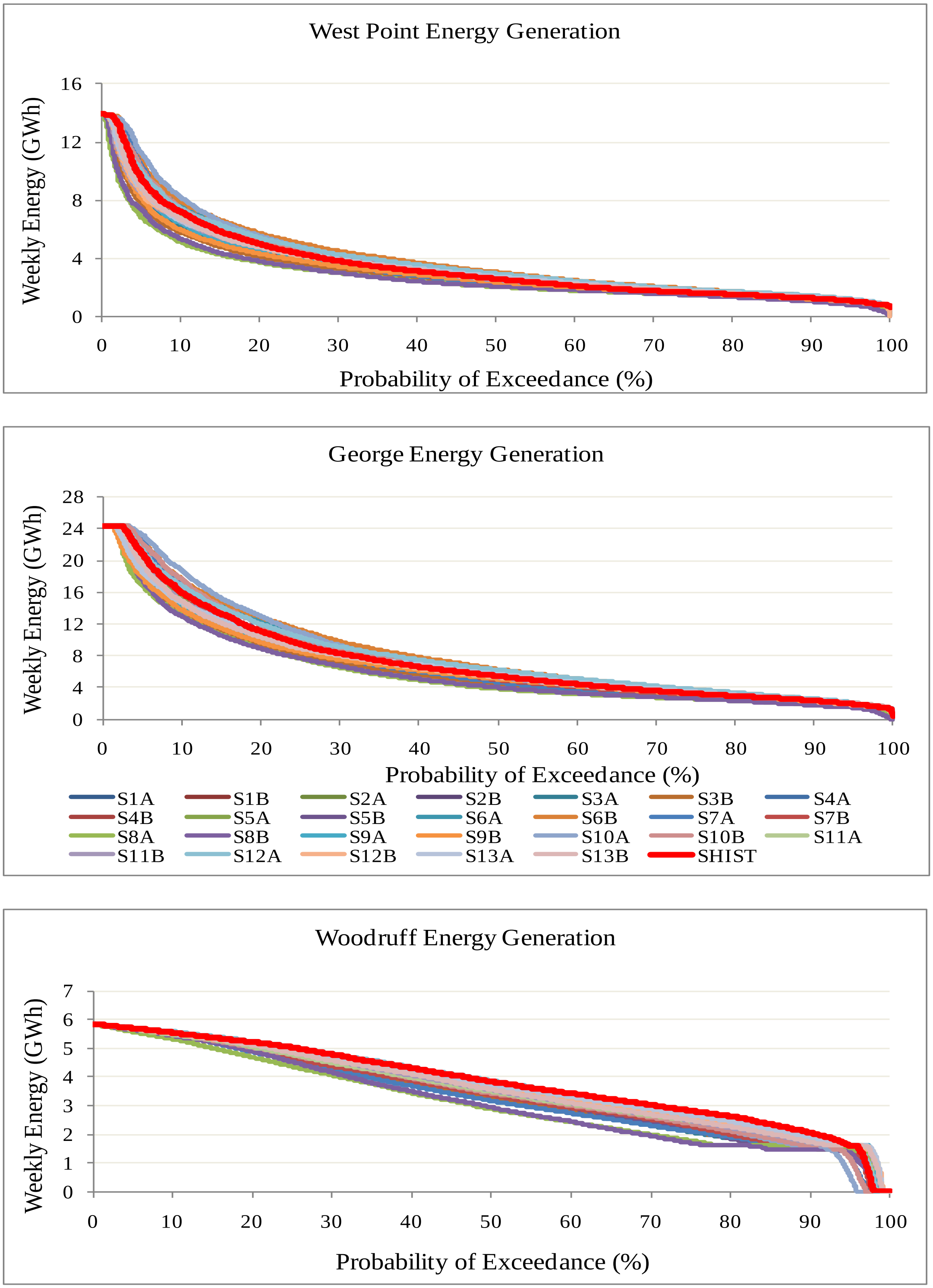
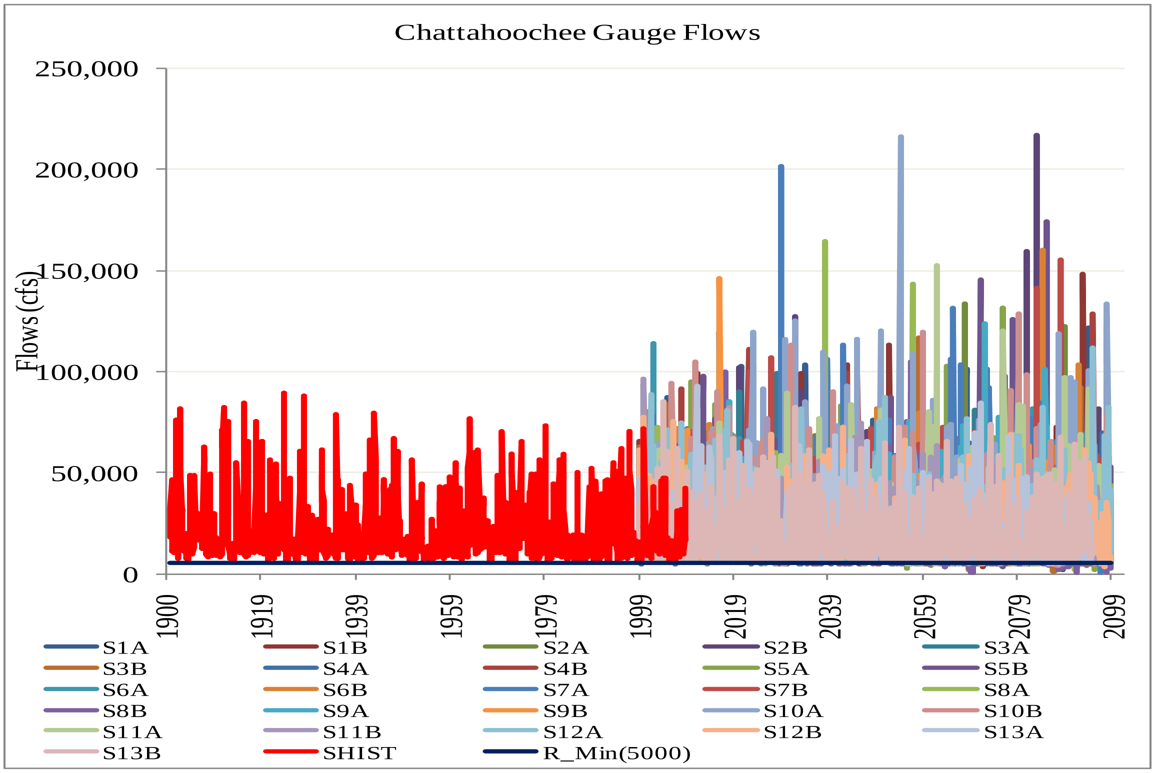


Figure 5.8: Hydropower Generation Duration Curves under Baseline Scenario (West Point, George and Woodruff)

5.1.1.4 Violation of Minimum In-stream Flow Requirements

One of the important water resources management objectives for the basin is to maintain minimum flows at several critical sections of the rivers to preserve water quality, safeguard the basin's environmental health and ecological integrity, and to protect the basin's unique aquatic biodiversity and endangered species. Under the current water resources management framework, specific minimum flow requirements have been designated at Atlanta (750 cfs), Whitesburg (1350 cfs), Columbus (1850 cfs), Andrews (2000 cfs), and Chattahoochee (5000 cfs). The water resources assessment model was used to assess the ability of the system to meet these minimum flow requirements under potential future water demand and climate change scenarios. Figure 5.9 shows flow conditions at the Chattahoochee gauge under historical and potential future climate change conditions. The figure shows that the minimum flow requirements are met at this river node most of the time except for some few violations observed under the driest climate scenarios especially toward the end of the assessment horizon. Figure 5.10 shows the number of violations of the minimum flow requirements at the different critical sections. The Chattahoochee section experiences the highest number of violations under all climate scenarios with up to 163 months over the entire assessment horizon under the driest climate scenario. The violations at Chattahoochee occur in 24 out of the 26 climate scenarios. The flow trends and minimum flow violations at the other critical sections are quite similar to Chattahoochee though less frequent and observed in fewer climate scenarios (Figure 5.11). Andrews experiences the least number of minimum flow violations.

The potential future violations, though infrequent, should be of concern to policy makers, especially since violations of such frequency have not been observed in the past. It is important to carefully assess and understand the implications and ecological impacts of these potential future violations and put in place appropriate mitigation measures to minimize their impacts.



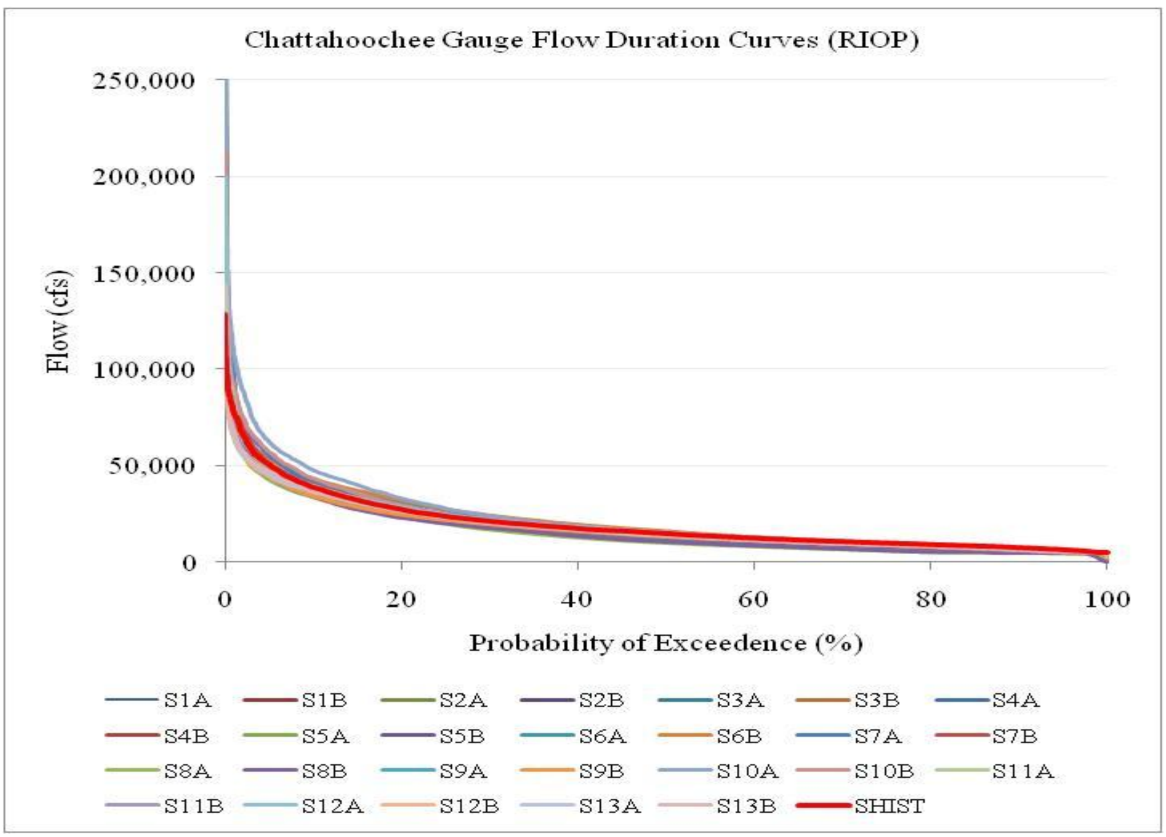


Figure 5.9: Chattahoochee Gauge Flows under Baseline Scenario

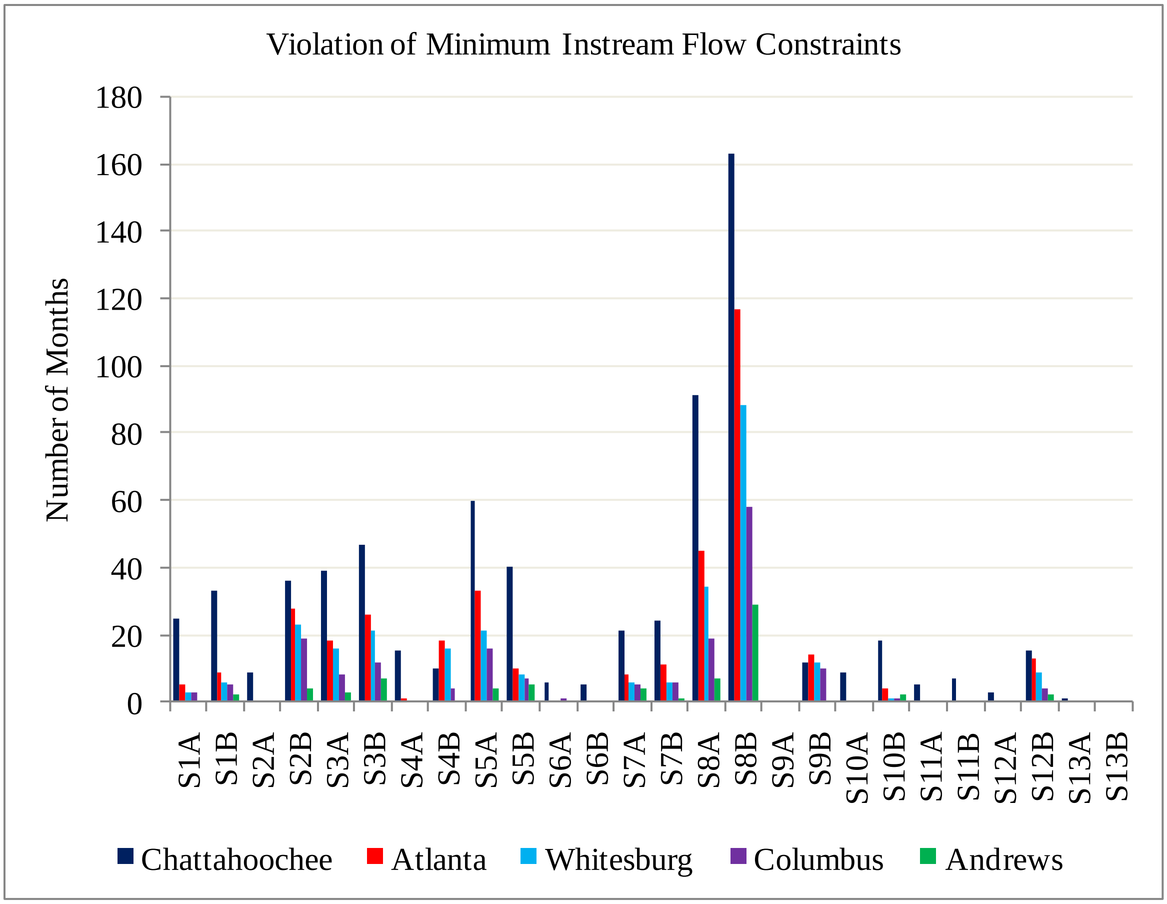


Figure 5.10: Violation of Minimum Flow Conditions under Baseline Scenario

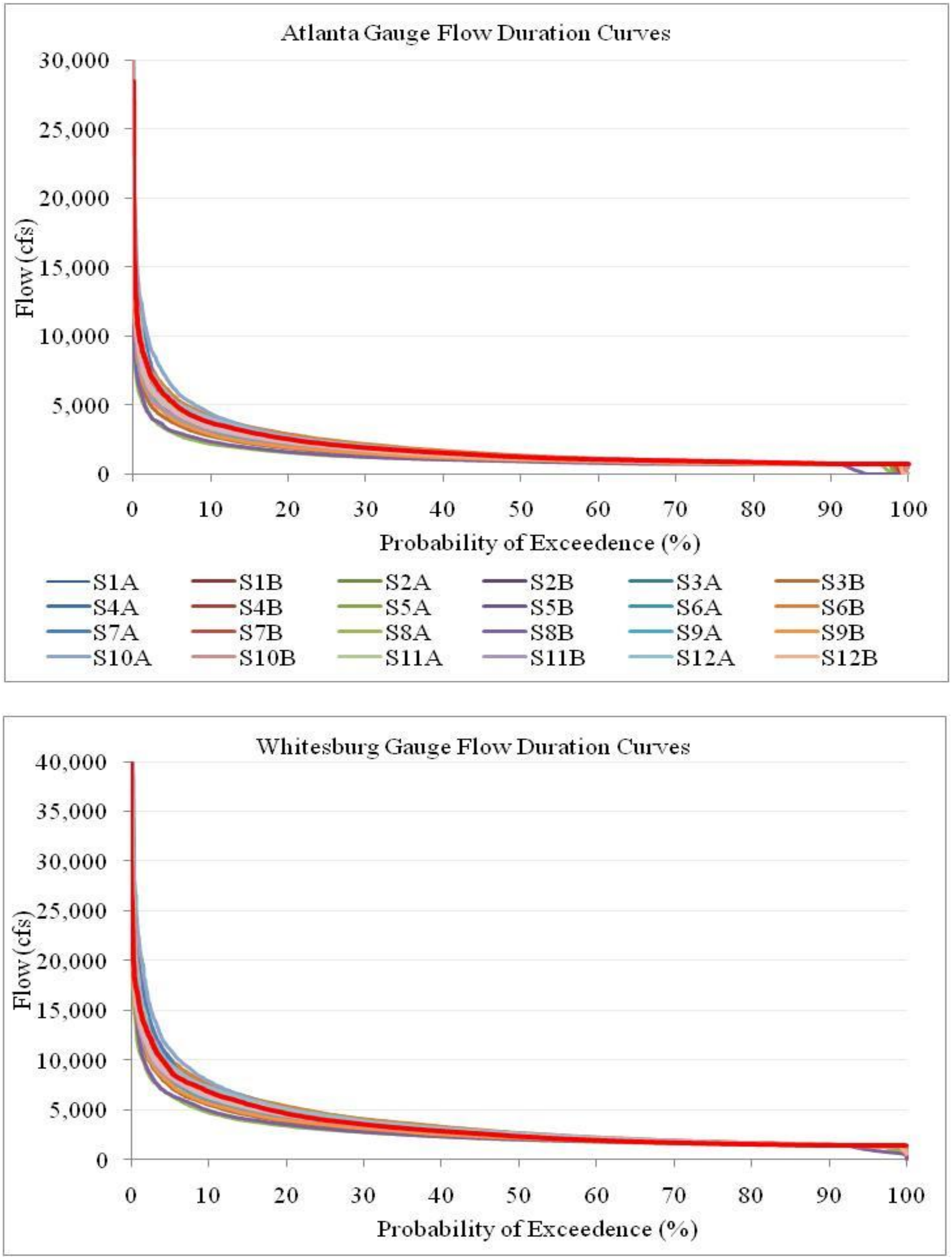
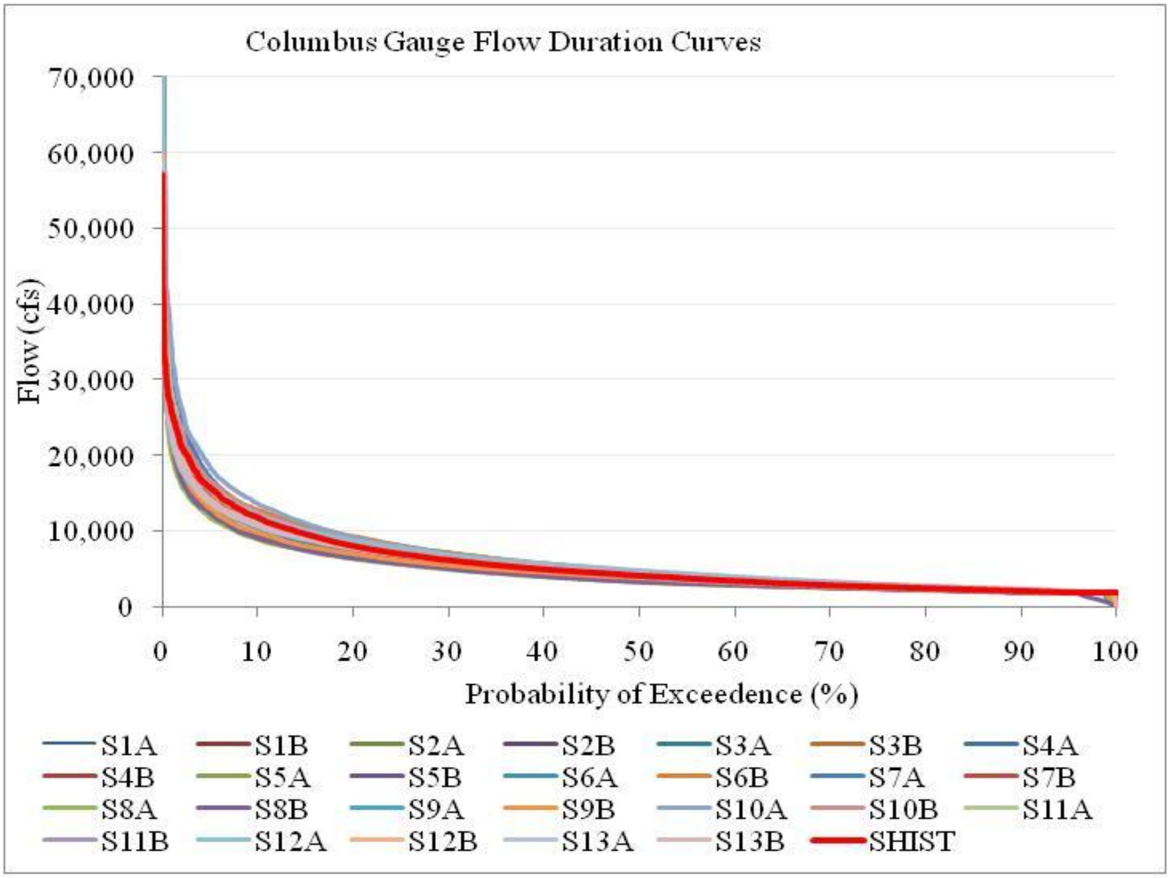


Figure 5.11: Flow Duration Curves for Critical Sections under Baseline Scenario



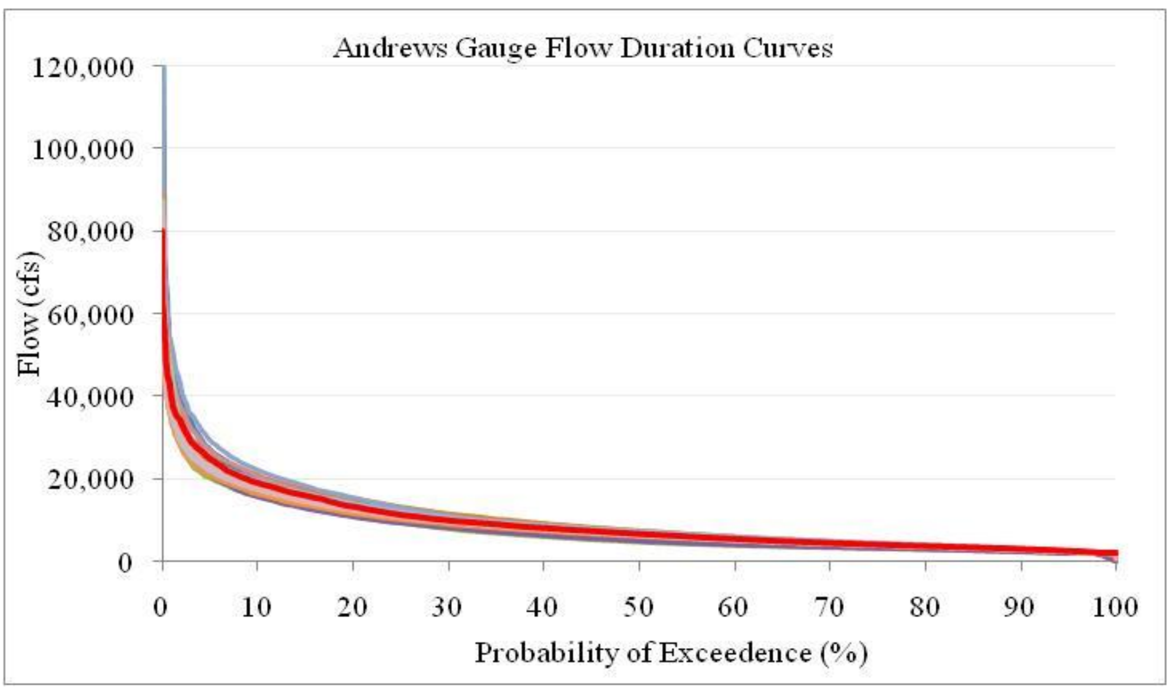


Figure 5.11 continued

5.1.2 Economic Benefit Assessments

5.1.2.1 Municipal Water Supply Benefits

Figure 5.12 shows the projected municipal water demands for the basin based on data from EPD (Georgia EPD, 2009). Demand is assumed to increase linearly from 2007 levels to the 2050 projected levels, after which the same linear trend is assumed to continue up to 2099. Figure 5.13 shows the annual Municipal water supply deficit computed by the water resources assessment model. The deficit varies from 0 to 390cfs depending on the climate change scenario. Most of the deficits occur during the later years of the assessment period due to increased water demands and the higher frequency of drought occurrence. The deficits are used by the Municipal water valuation model to compute the corresponding Municipal water supply loss.

It is assumed here that there are no alternative sources of cheap municipal water supply and that consumers have to consume less water than desired due to supply shortages. Regulated water utility companies usually do not raise prices during a supply shortage to reach market equilibrium. The price ceilings thus result in excess demand during a shortage. Consumers are usually willing to pay considerably more than what regulated utility companies charge them for municipal water supply, particularly if the alternative were water shortages. The difference between what consumers are willing to pay and what they are actually charged is referred to as consumer surplus. Figure 5.14 shows the annual Municipal water supply loss. The annual loss varies from 0 to $ 120 million.

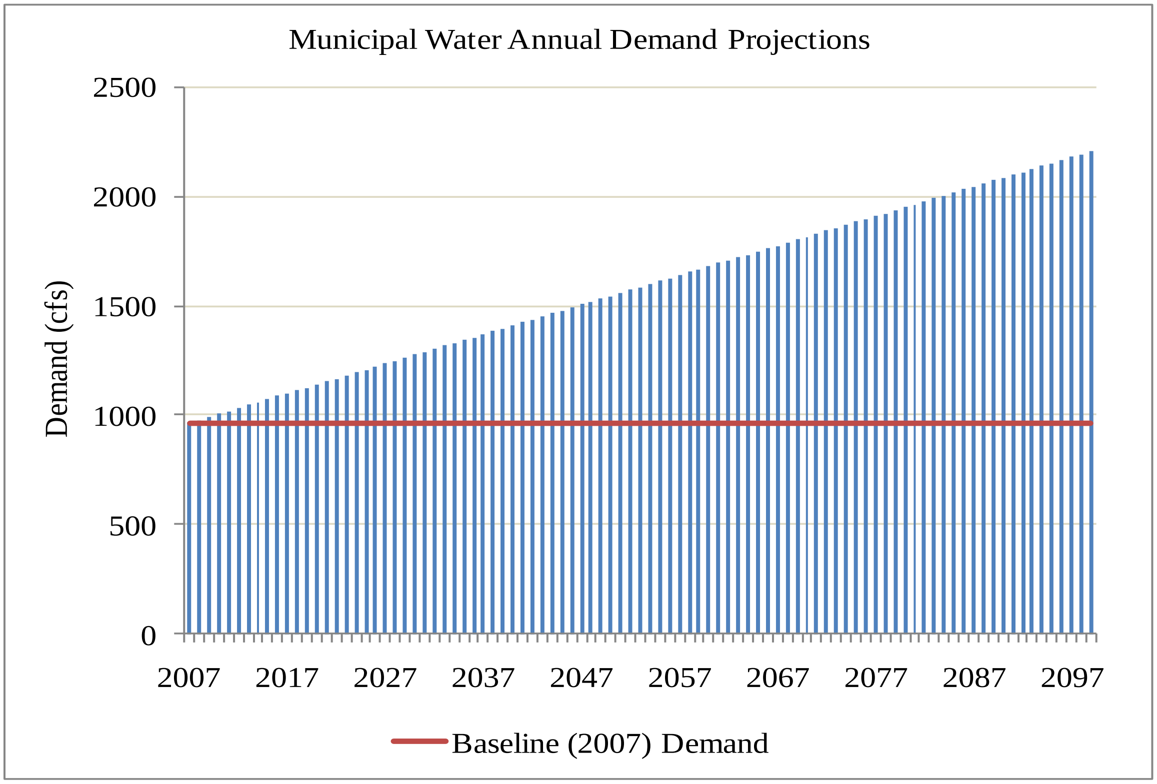


Figure 5.12: Municipal Water Annual Demand Projection

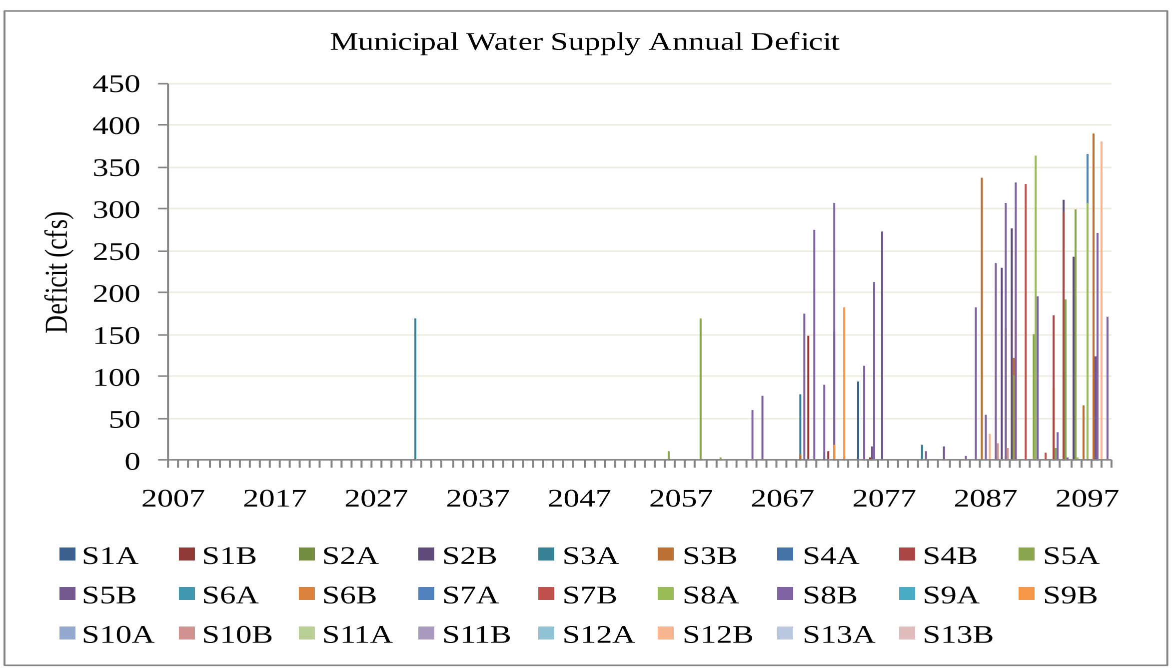


Figure 5.13: Municipal Water Supply Annual Deficit under Baseline Scenario

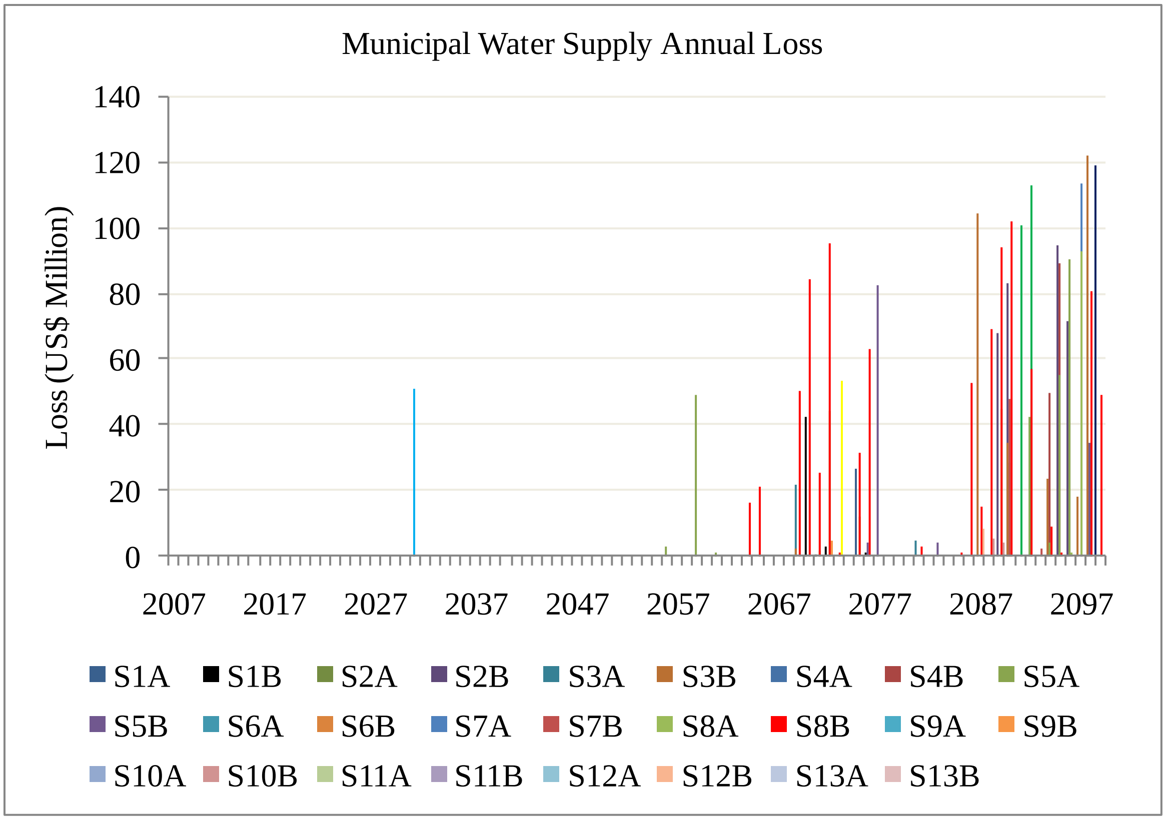


Figure 5.14: Municipal Water Supply Annual Loss under Baseline Scenario

5.1.2.2 <u>Hydropower Water Use Benefits</u>

Figure 5.15 shows the annual hydropower generation bounds for all the 26 climate change scenarios considered. The total annual energy varies between 324GWh to 3414GWh depending on climate conditions. Figure 5.16 shows minimum and maximum bounds for the annual incremental (from base year, 2007) hydropower benefits under all climate scenarios. They vary from -$104 to $96 million depending on climate conditions. The figure shows a steady decline in mean annual benefits attributed to declining lake levels over time due to the steady increase in consumptive water withdrawals and increased frequency of drought conditions in the later part of the century.

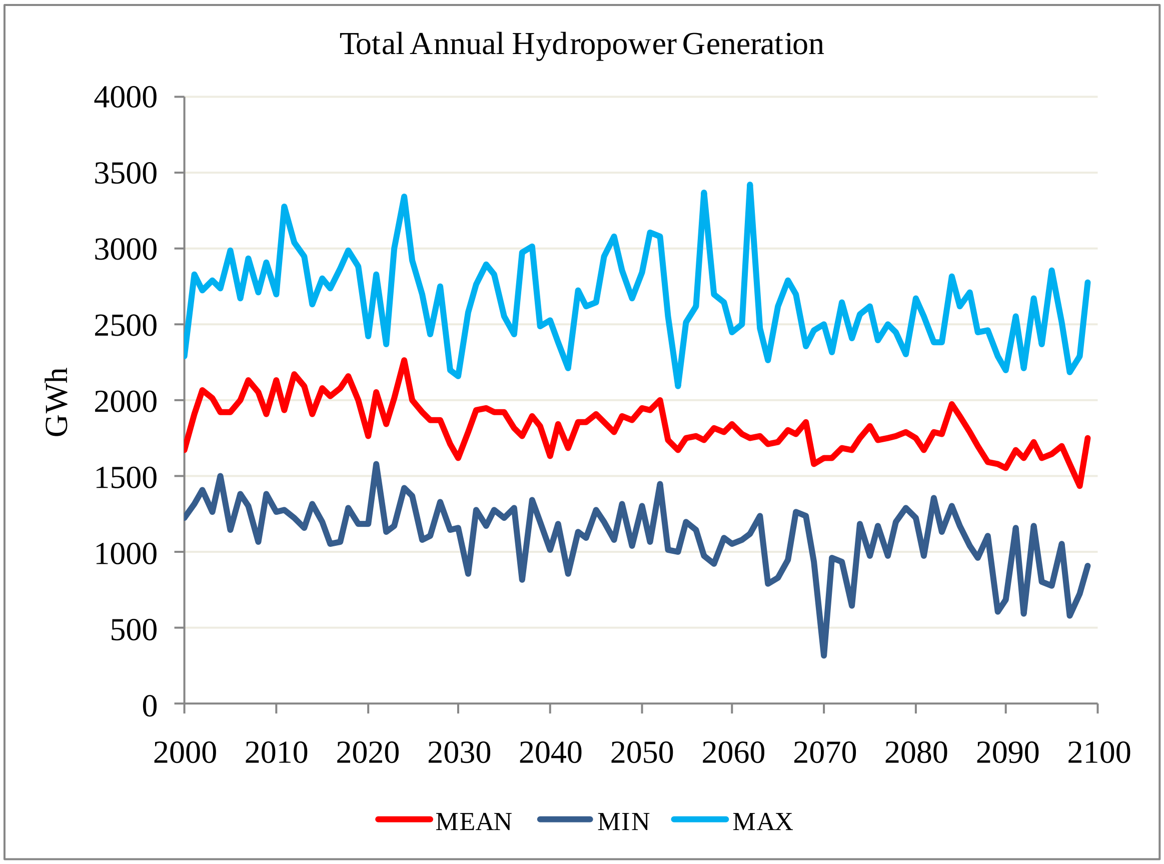


Figure 5.15: Annual Hydropower Generation Bounds under Baseline Scenario

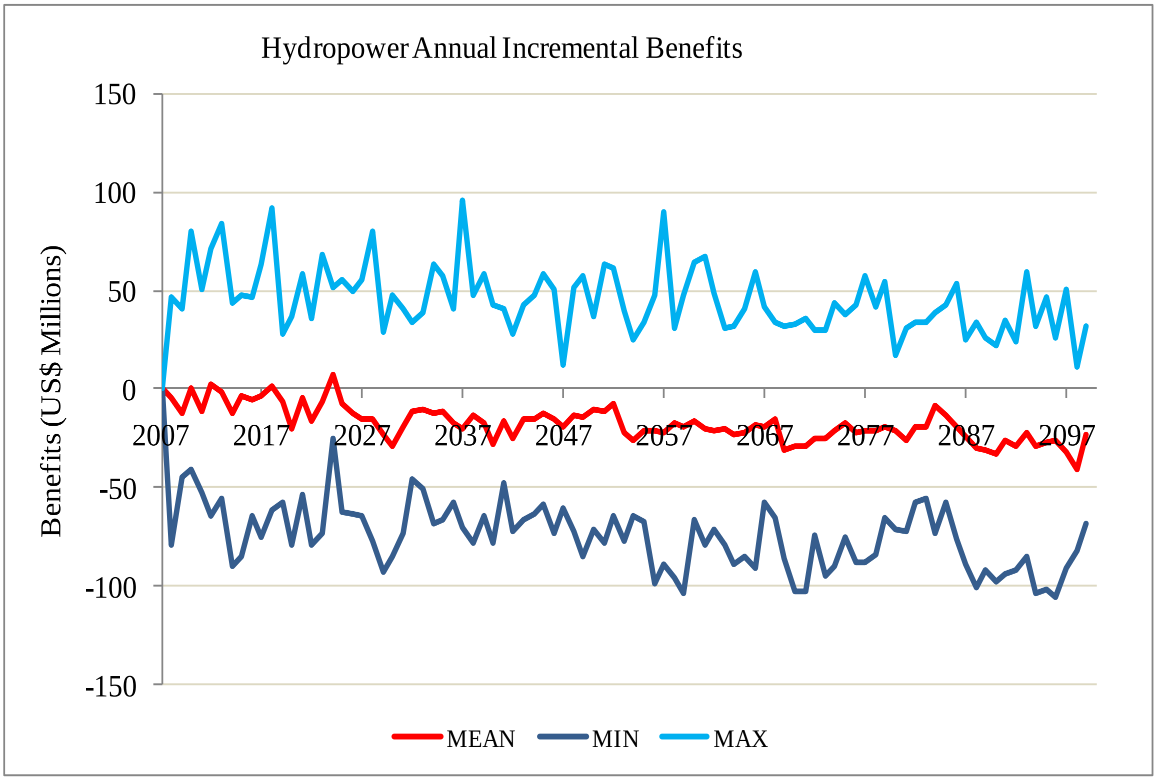


Figure 5.16: Hydropower Annual Benefits under Baseline Scenario

5.1.2.3 Recreation Water Use Benefits

Figure 5.17 shows minimum and maximum bounds for recreation annual incremental benefits for all climate change scenarios. They range from -$200 million to $79 millions. The figure also shows a steady decline in mean annual incremental benefits over the assessment horizon due to increased frequency of low lake levels over time. This is attributed to the steady increase in consumptive water withdrawals and also increased frequency of drought conditions over the years.

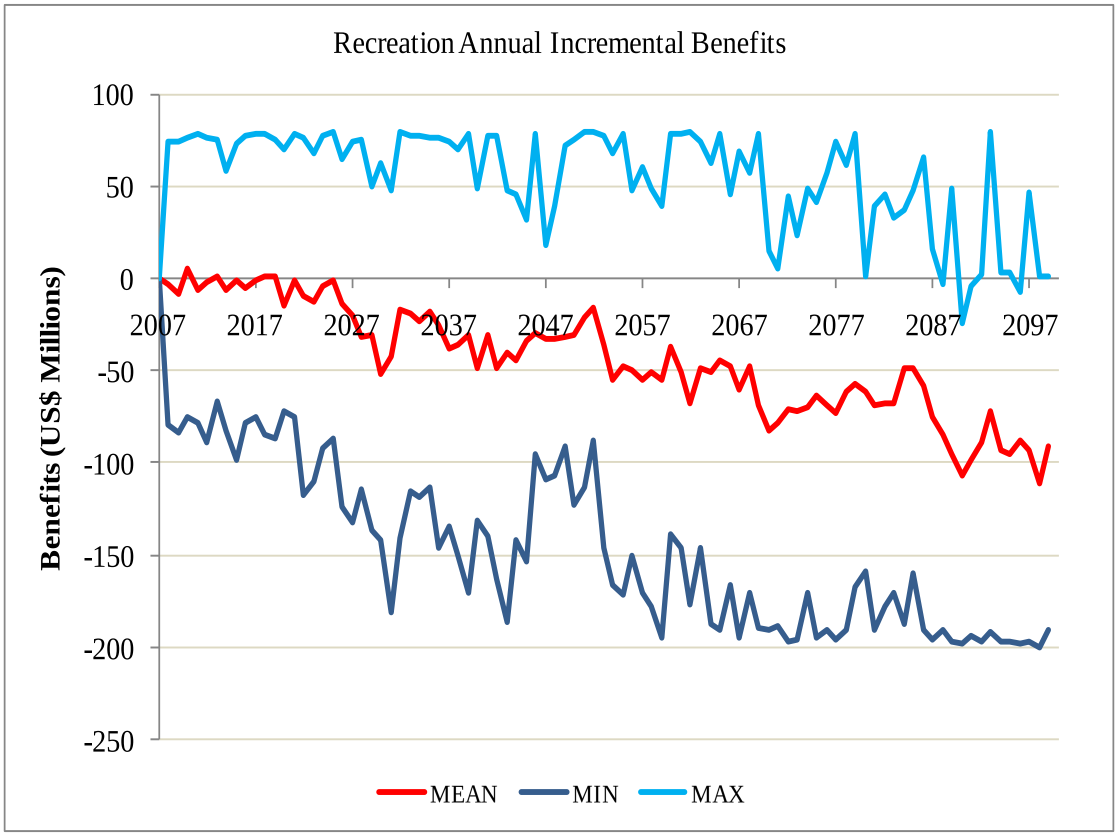


Figure 5.17: Recreation Annual Benefits under Baseline Scenario

5.1.2.4 <u>Irrigation Water Use Benefits</u>

Estimation of irrigation benefits in this case is associated with minimization of irrigation water supply costs. The underlying assumption is that farmers in the Flint River basin have the option of either using surface or groundwater to meet their irrigation demands, with groundwater being the marginal source associated with higher costs of pumping compared to surface water. The existence of an alternative to surface water puts an upper limit on the loss farmers would incur due to surface water shortages. Farm-level pumping costs for additional groundwater to meet the surface water deficit, therefore, serve as the proxy of estimates of losses that farmers would incur due to surface water shortages. The other assumption here is that groundwater is available in sufficient quantities to meet increasing irrigation demands over the assessment horizon. No attempt is made to assess the implications of the increased groundwater pumping on river flows though this may be significant in some river sections especially during the very dry years. Figure 5.18 shows the projected surface water irrigation demands for the basin based on data from EPD (Georgia EPD, 2009). Demand is assumed to increase linearly from 2007 levels to the 2050 projected levels, after which the same linear trend is assumed to continue up to 2099. The same growth trend assumption is applied to the water return ratio. Figure 5.19 shows the annual irrigation water supply deficit computed by the water resources assessment model. The deficit varies from 0 to 14.5cfs depending on the climate change scenario. Most of the deficits occur during later years of the assessment period due to increased water demands and higher frequency of occurrence of drought conditions. The deficits are used by the irrigation water valuation model to compute the corresponding additional irrigation water supply costs. Figure 5.20 shows additional annual irrigation water supply costs. The costs range from 0 to $ 0.12 million.

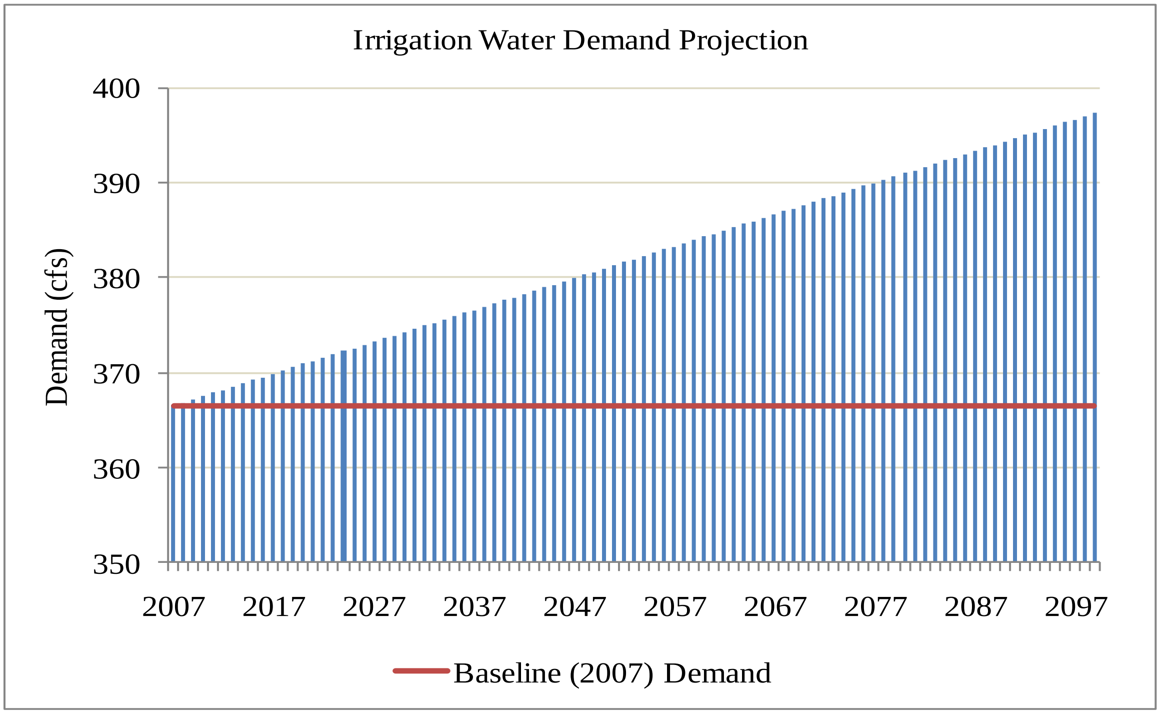


Figure 5.18: Surface Water Irrigation Demand Projection

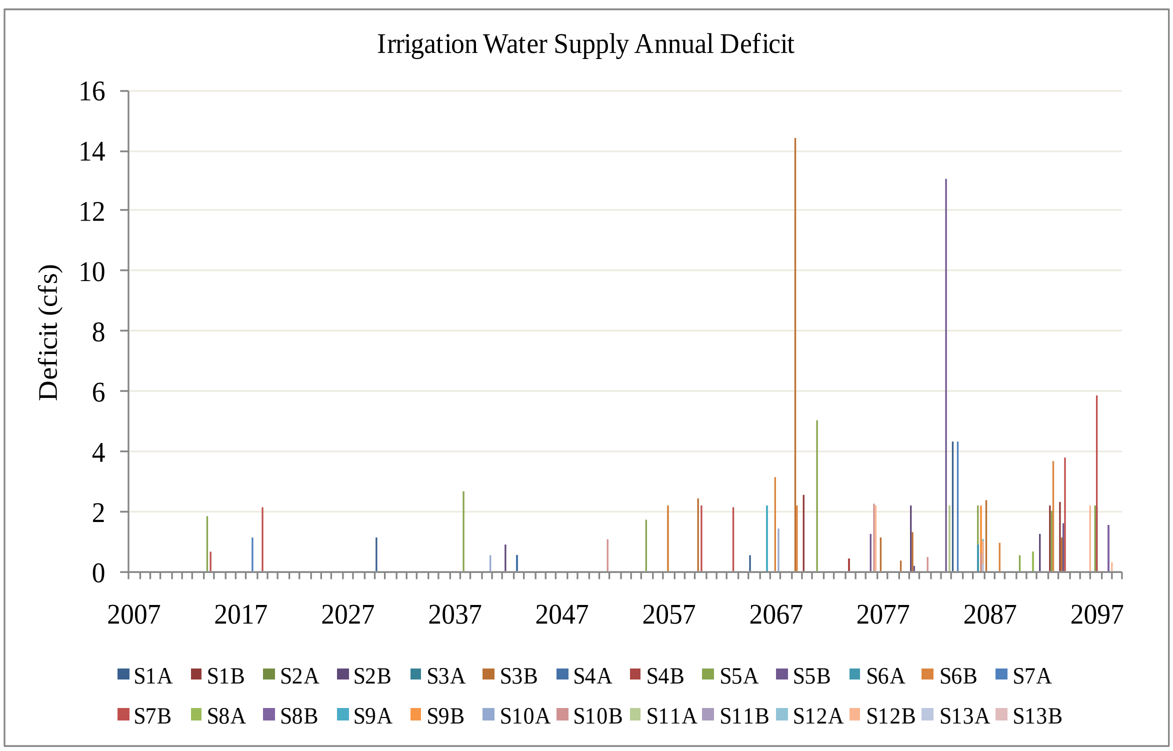


Figure 5.19: Irrigation Water Supply Annual Deficit under Baseline Scenario

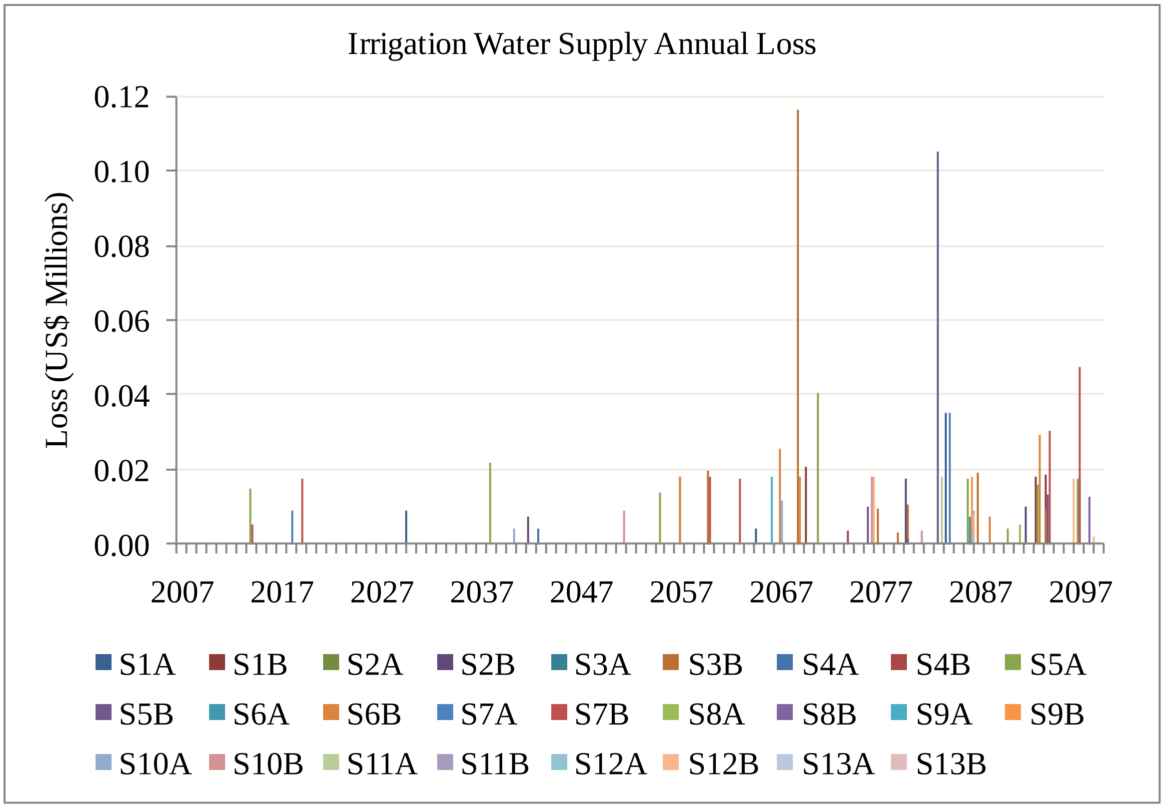


Figure 5.20: Irrigation Water Supply Annual Loss under Baseline Scenario

5.1.2.5 <u>Thermal Cooling Water Benefits</u>

There are no annual incremental cooling water benefits because cooling water requirements are met all the time.

5.1.3 Summary of Findings

The baseline assessment highlights the changes in system performance over the next 100 years due to increasing pressure on the basin's water resources. The basin is expected to experience reduction in water supply and increase in water demand due to climate and demographic changes. The basin is most likely to experience significant reduction in runoff from its watersheds due to projected increase in evapotranspiration associated with higher temperatures in future. Water demand projections indicate a significant increase in water demand due to population increase. Most of the demand increase is expected to be in the municipal water supply sector with a smaller increase expected in irrigation water demand. However, due to planned investments in efficient water use technologies and improved return flow drainage infrastructure, return flows are expected to increase resulting in minimal changes in aggregate consumptive water use in the sector. Decreased watershed runoff will have a negative impact on reservoir levels and associated non-consumptive water uses that rely on them (e.g. hydropower generation and recreation).. It is therefore important that water managers and decision makers begin considering these challenges and formulate appropriate intervention measures that will address these challenges in the years to come and minimize their impacts. This will require consideration of a mixture of intervention measures ranging from reviewing existing water resources management policies in the basin to investment in water infrastructure, research, and efficient water use technologies. The next chapter considers some of the existing management objectives and policies in the basin that could potentially be reviewed and improved and also demonstrates the benefits that would accrue from implementation of the proposed policy changes.

5.1.4 Assessment of Economic versus Physical Uncertainty

Assessment of the implications of economic uncertainty on projections of economic benefits is demonstrated for the hydropower generation sector. The GBM technique was used to forecast energy prices up to the year 2099. The volatility used was computed from historical energy prices. Figure 5.21 shows the energy price forecasts based on 100 Monte Carlo simulations. The energy price forecast ranges between 0 to $ 340 per MWh over the assessment period. The price forecasts were used to compare the economic benefits of hydropower generation in the basin under two alternative reservoir operation policies discussed in previous sections (RIOP and GTOP). The assessment was based on a mean hydropower generation trace computed from 26 climate change scenarios and 30 price forecast traces. Figures 5.22 show annual hydropower benefits corresponding to the two policies. Comparison of these figures with those obtained earlier based on 26 climate change scenarios and the mean energy price trace shows differences in the degree of variability of the annual hydropower benefits in the two cases. Under multiple price forecast traces, the annual hydropower benefits range between 0 to $ 350 million while the range corresponding to multiple climate change scenarios is $30 million to $ 180 million. This assessment shows that uncertainty in future economic parameters can have a bigger bearing on projection of future water use benefits than hydro-climatic uncertainty. Similar assessments carried out for the other water use sectors yielded the same conclusion. This finding highlights the need for careful characterization of both physical and economic uncertainty in long-term hydro-economic assessments of this nature. Assessments in the next chapter consider both physical and economic uncertainty. In computing sectoral water use benefits/losses, multiple (30) price forecast traces are used in conjunction with multiple (26) climate change scenarios to give a wide range of uncertainty characterization.

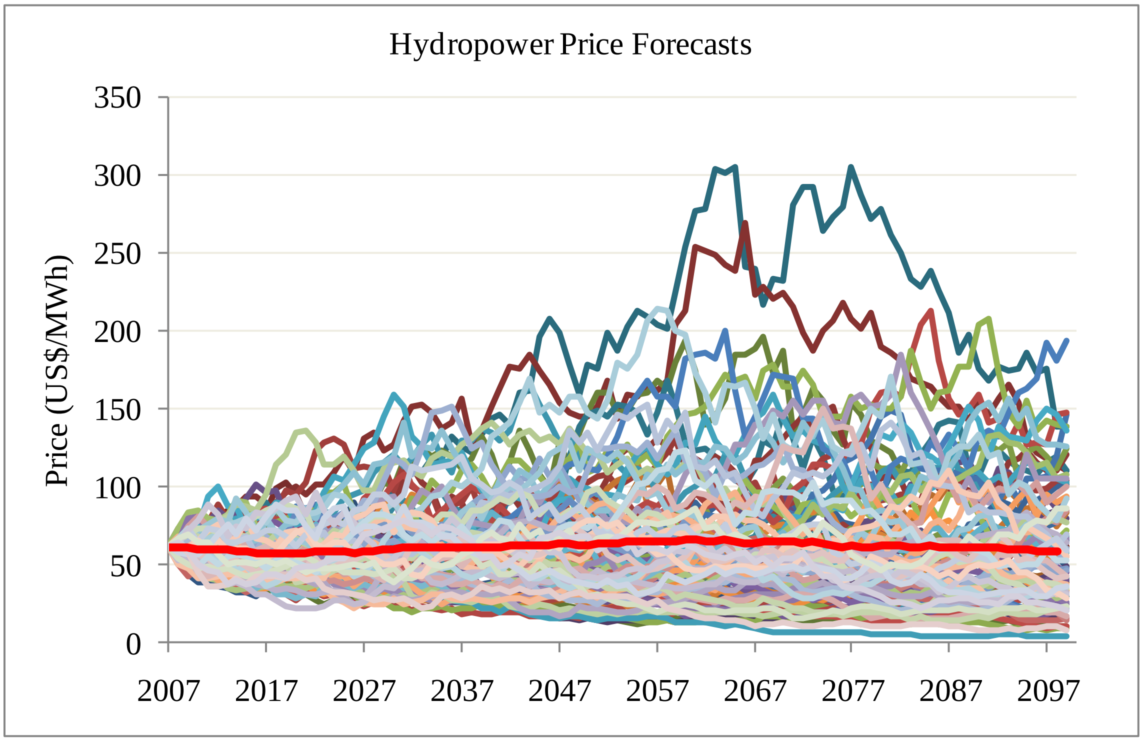
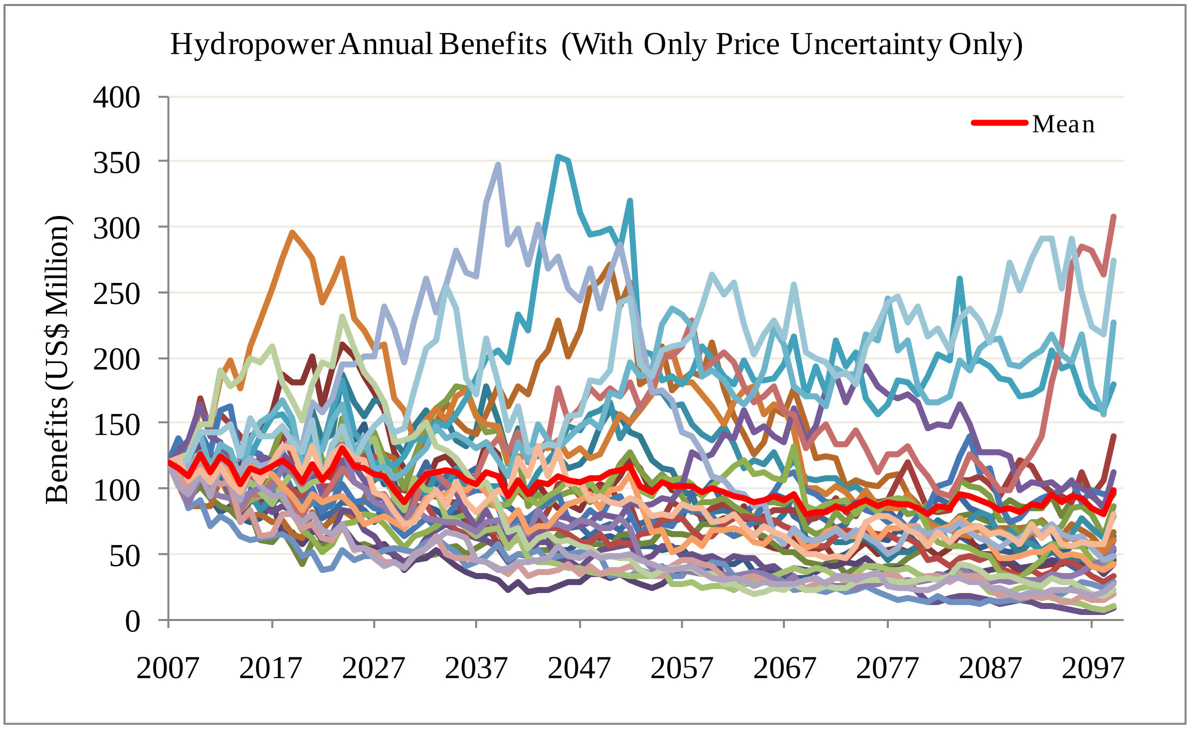


Figure 5.21: Hydropower Price Forecast



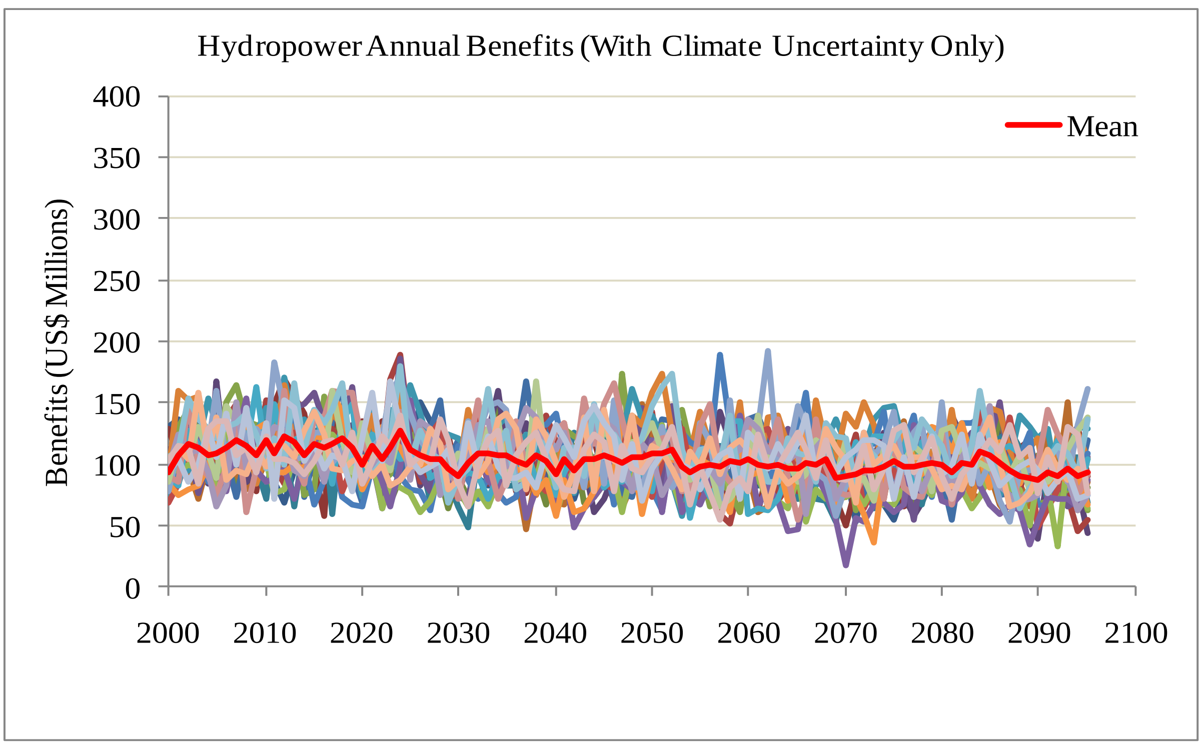


Figure 5.22: Comparison of Hydropower Annual Benefits (Economic versus Climate Uncertainty)

CHAPTER 6: WATER RESOURCES POLICY ASSESSMENTS

Chapter 5 presented an assessment of the performance of the ACF system under potential water demand growth and future climate change scenarios. The assessment was based on existing management objectives, reservoir operation policy, minimum flow requirements at specific river sections, and other physical constraints of the system. However, as water demands continue to grow and other pressures on the system increase in the future, there will be need to review current management objectives, reservoir operation policies, and other operational constraints to improve water use efficiency and cope with the emerging water resources management and allocation challenges. Water resources management reform processes can be complex and protracted due to the multitude of stakeholder groups involved with conflicting interests. It is therefore important that the process is conducted in a transparent and fully participatory manner based on technically sound data and information on all potential policy options. Some of the potential policy options for the ACF could include, among others, (a) review of the existing reservoir operation policy and replace it with a more efficient one; (b) review of the current minimum flow requirements imposed at specific river sections to ensure a healthy balance between upstream water use and sustainability of aquatic ecosystems downstream; and (c) water supply restrictions. Assessment of physical and economic implications of such potential policy changes requires robust technical tools with the ability to adequately represent the complex physical characteristics of the system and corresponding water management objectives and socio-economic conditions. Hydro-economic tools are well suited for such assessments as they address both the physical and economic performance of the system.

In this chapter, the physical and economic performance of the ACF system under three potential water management scenarios is assessed. For each management scenario, physical and economic performance of the system is benchmarked against the “baseline” management scenario discussed in Chapter 5. The economic assessments undertaken are therefore based on potential policy changes and the results should be interpreted in that respect. The assessment proceeds by first determining the physical outputs of the system corresponding to the proposed management scenario, followed by comparison of these outputs with those under the “baseline” management scenario to determine the change in physical outputs attributed to the proposed management scenario. The two sequences of physical outputs are then used as inputs into the economic assessment model to determine the basin-wide economic benefits/losses corresponding to the policy change. Basin-wide benefits are estimated by aggregating sectoral water use benefits/losses accruing to different water use sectors, i.e., municipal water use, irrigation, recreation, hydropower generation, and thermal energy generation cooling water use. The economic assessments are based on the sectoral water use valuation methods discussed in Chapter 3. The three assessment scenarios considered are designed to address the following important water resources management and use questions:

(i) What are the economic benefits of alternative reservoir operation policies?

(ii) What is the opportunity cost of environmental flow?

(iii) What are the economic implications of water supply restrictions?

6.1 Policy Scenario 1: Implementation of Alternative Reservoir Operation Policy

6.1.1 Background

This section presents a comparison of the physical and economic performance of the ACF system under the current and alternative reservoir operation policies (RIOP and GTOP). The Scenario assessment model of the ACF DSS is used to evaluate the performance of the ACF system under the two policies subject to future water demand and climate change, and existing environmental flow requirements and other system constraints. Sequences of physical outputs generated by the model include reservoir levels, inflow and release sequences for all storage facilities, water withdrawals at all nodes, and weekly energy generation sequences at all hydropower facilities in the basin. These sequences are used to compare the changes in the physical outputs of the system under the two policies. They are also used as inputs into the economic assessment models that are used to estimate the corresponding changes in economic benefits. Discussion of the results follows.

6.1.2 Assessment of Change in Physical Outputs

6.1.2.1 Fluctuation of Reservoir Water Levels

Figure 6.1 shows Lake Lanier water level fluctuation under RIOP and GTOP. Under the GTOP, several future frequency curves fall above the historical frequency curve implying that the lake is more likely to experience higher water levels under future climate conditions. In contrast, under the RIOP, all future frequency curves fall below the historical curve indicating that the lake is most likely to experience lower water levels under future climate conditions. This is attributed to the flexibility in the GTOP which enables storage of more water during wet seasons to augment dry season low levels. Figure 6.2 shows the frequency of reservoir depletion over the assessment horizon. Lake Lanier experiences a higher frequency of reservoir depletion under RIOP compared to GTOP. The frequency of depletion associated with RIOP varies from 0 to 13 months depending on the climate change scenario. The corresponding frequency is 0 to 12 months under the GTOP. The lake experiences full depletion in fewer climate scenarios (10 out of the 26 scenarios) under GTOP compared to RIOP (12 out of the 26 scenarios). The other reservoirs follow the same pattern as Lake Lanier but with lower frequency and over fewer climate scenarios, except West Point which does not experience reservoir depletion.

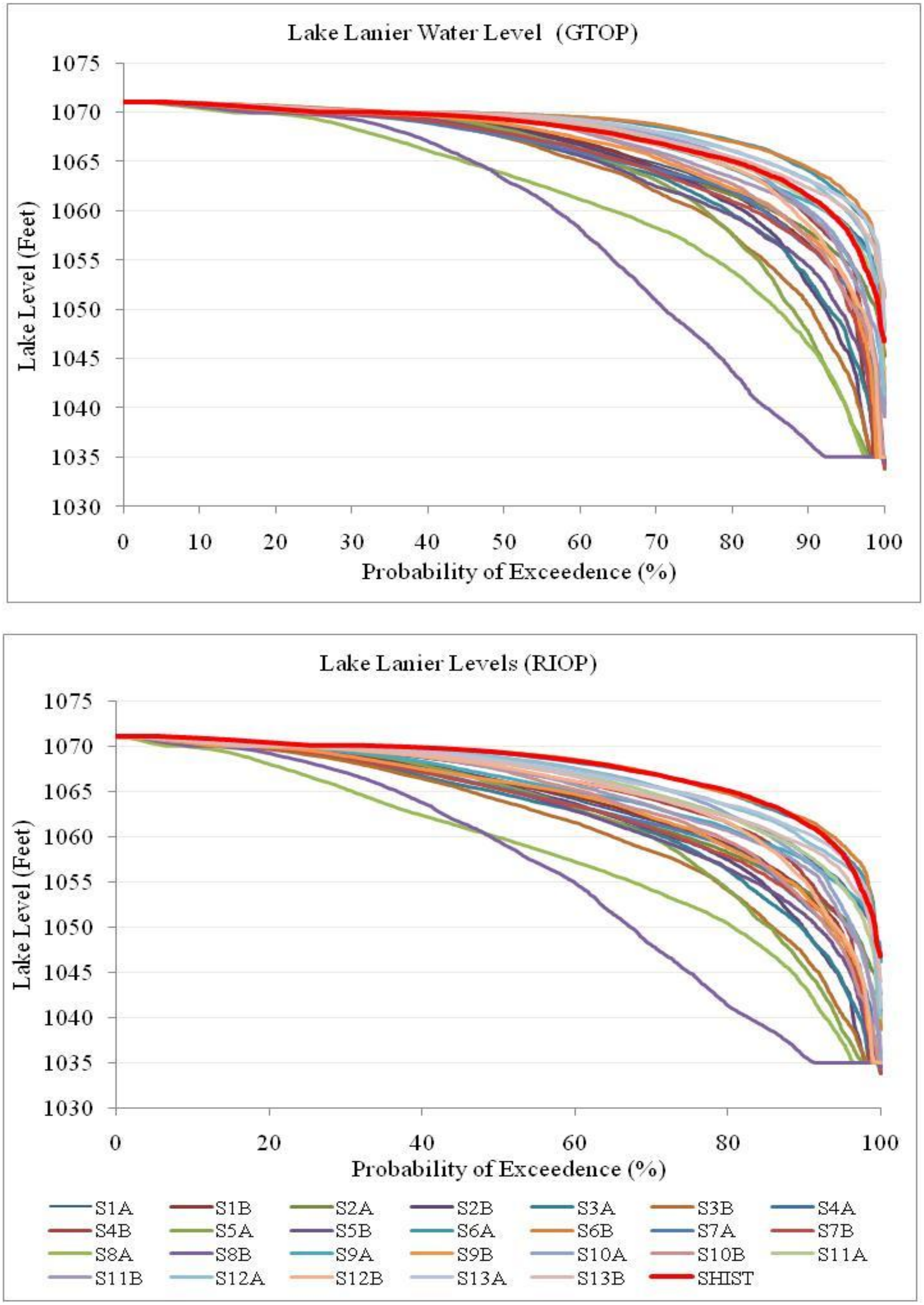


Figure 6.1: Lake Lanier Water Level Duration Curves (GTOP versus RIOP)

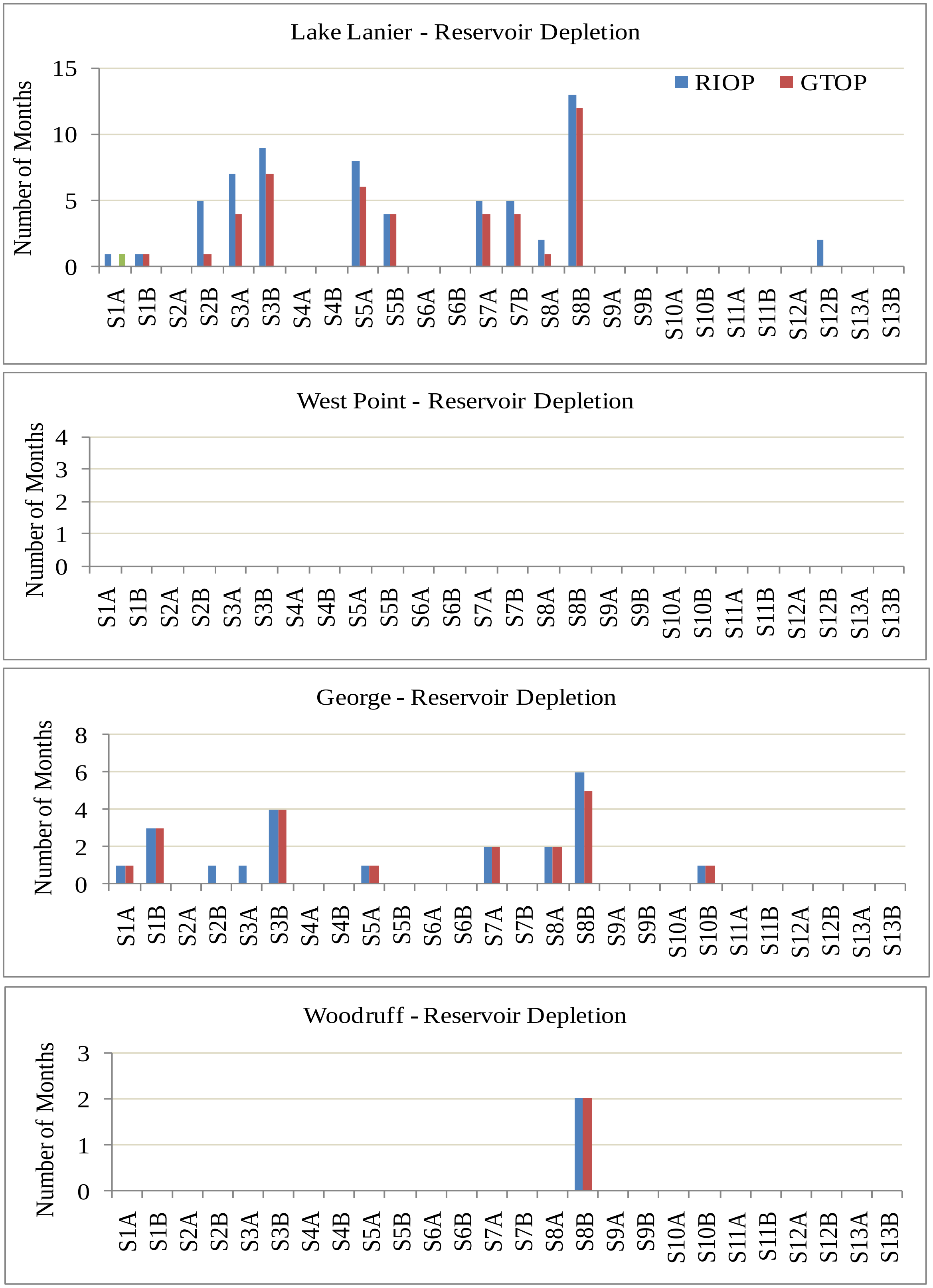
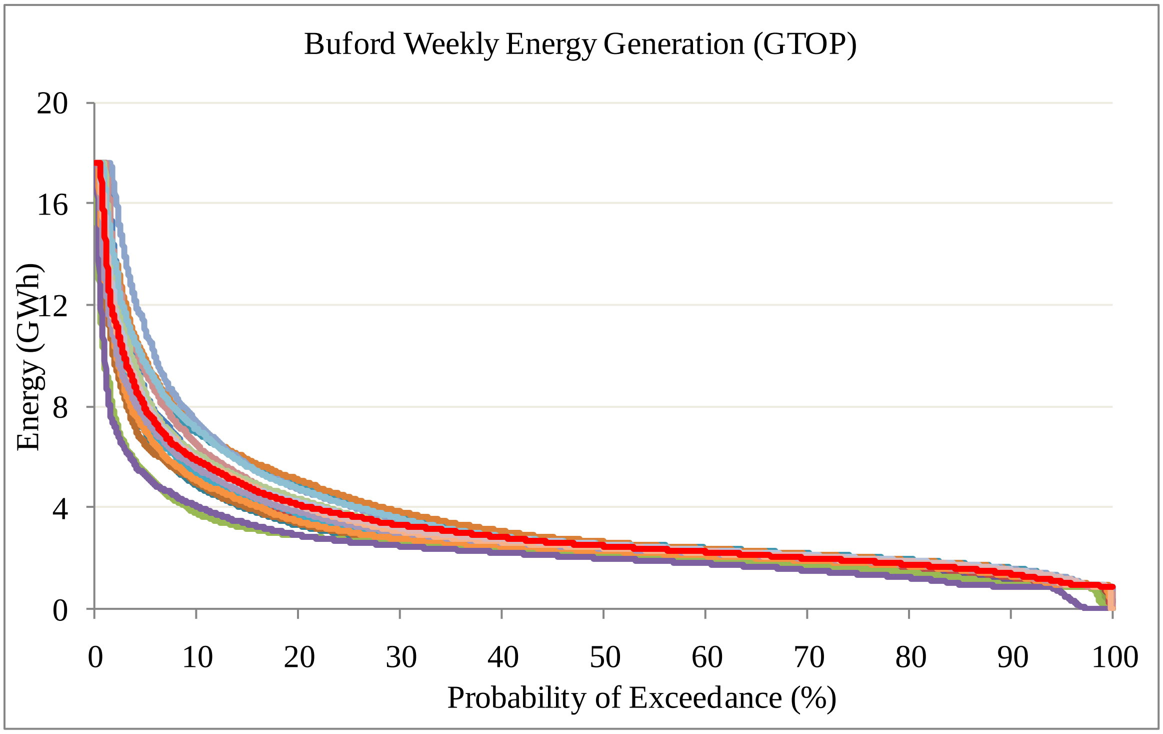


Figure 6.2: Potential Reservoir Depletion (GTOP versus RIOP)

6.1.2.2 Variability in Hydropower Generation

Figures 6.3 shows Buford hydropower generation and the corresponding power frequency curves under the two policies. There is no significant difference between the two policies in terms of energy generation. For example the mean annual total energy generation for all plants in the basin over the entire assessment period is 1830 GWh for RIOP and 1826 GWh for GTOP. For the driest climate scenario the mean annual energy generation is 1540 GWh under both policies while the corresponding values under the wettest scenario are 2084 GWh for GTOP and 2088 GWh for RIOP. Figure 6.4 shows the frequency of hydropower generation failure under both policies. The frequency of energy generation failure is higher under RIOP compared to GTOP except under the driest climate scenario. This is expected because RIOP is associated with higher frequency of reservoir depletion as discussed above. George follows the same pattern as Lake Lanier but with lower frequency and over fewer climate scenarios. West Point experiences no generation failures over the entire assessment period while Woodruff experiences the most frequent failures under most climate scenarios (24 out of 26).



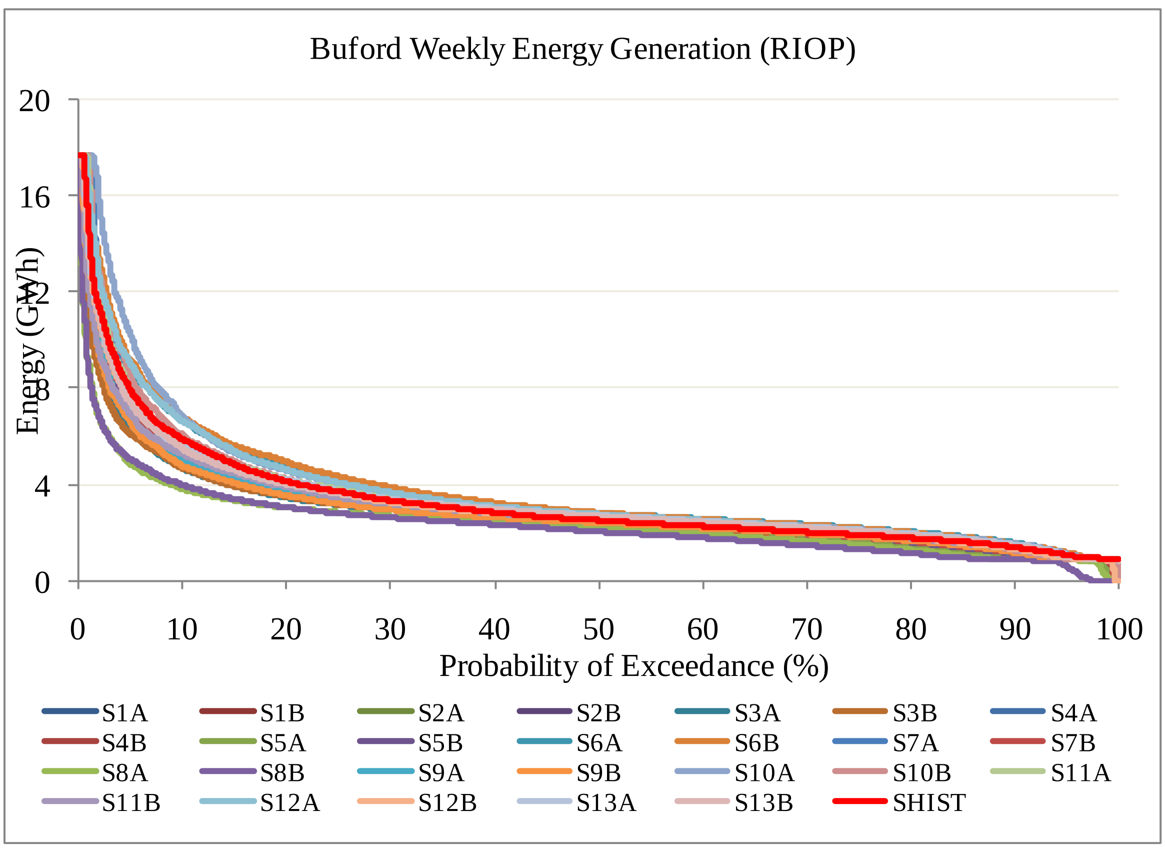


Figure 6.3: Buford Hydropower Generation Frequency Curves (GTOP versus RIOP)

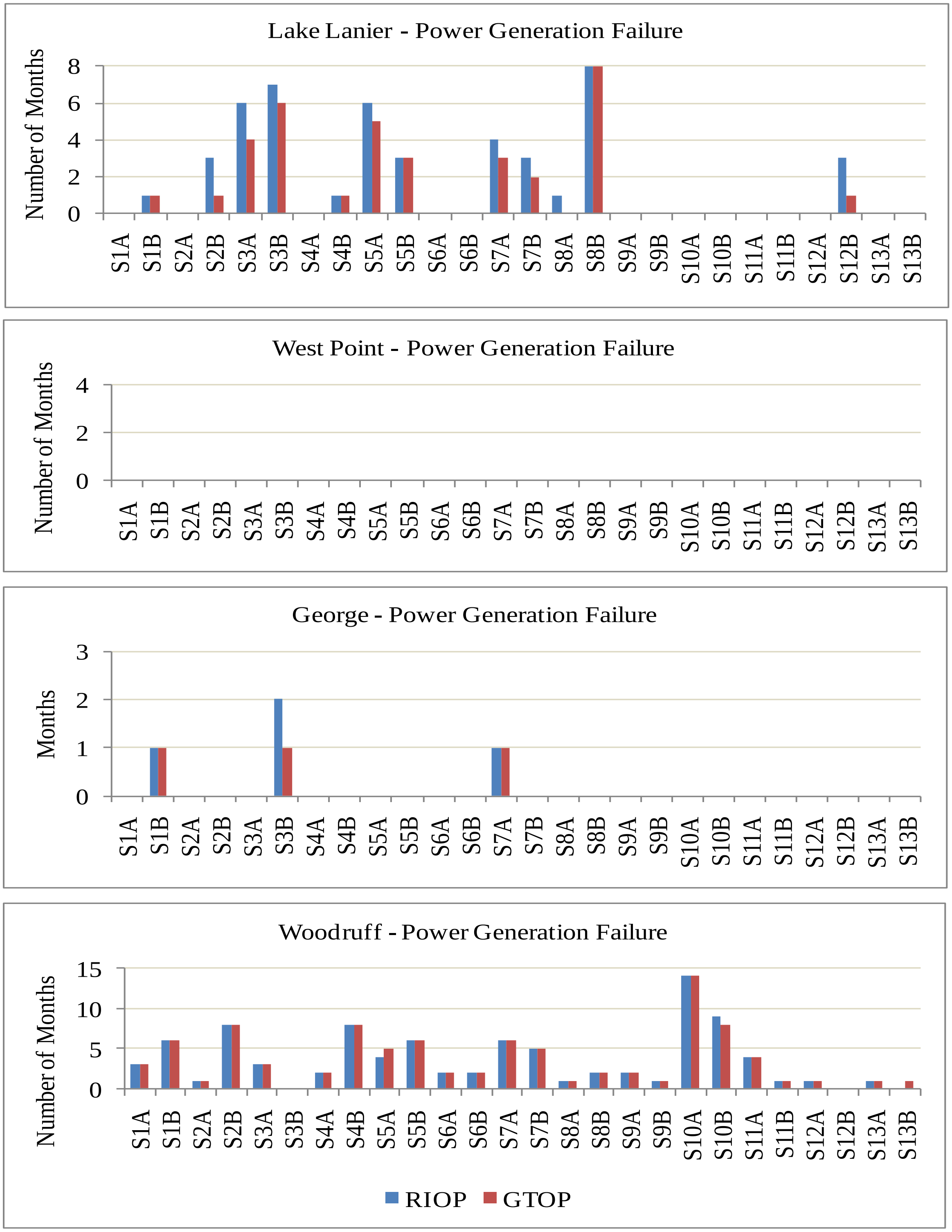


Figure 6.4: Potential Hydropower Generation Failure: West Point, George, Woodruff (GTOP versus RIOP)

6.1.2.3 Violation of Minimum In-stream Flow Requirements

Figure 6.5 shows the frequency of violation of the environment flow requirement at the Chattahoochee gauge. The figure shows more violations under RIOP compared to GTOP. The violations range from 0 to 163 months under the RIOP and 0 to 146 months under the GTOP over the entire assessment period, depending on the climate change scenario. The violations occur in 22 out of the 26 climate scenarios under the GTOP and in 24 of the climate scenarios under RIOP. The monthly flows at the Chattahoochee gauge and corresponding frequency curves are shown in Figure 6.6**.**

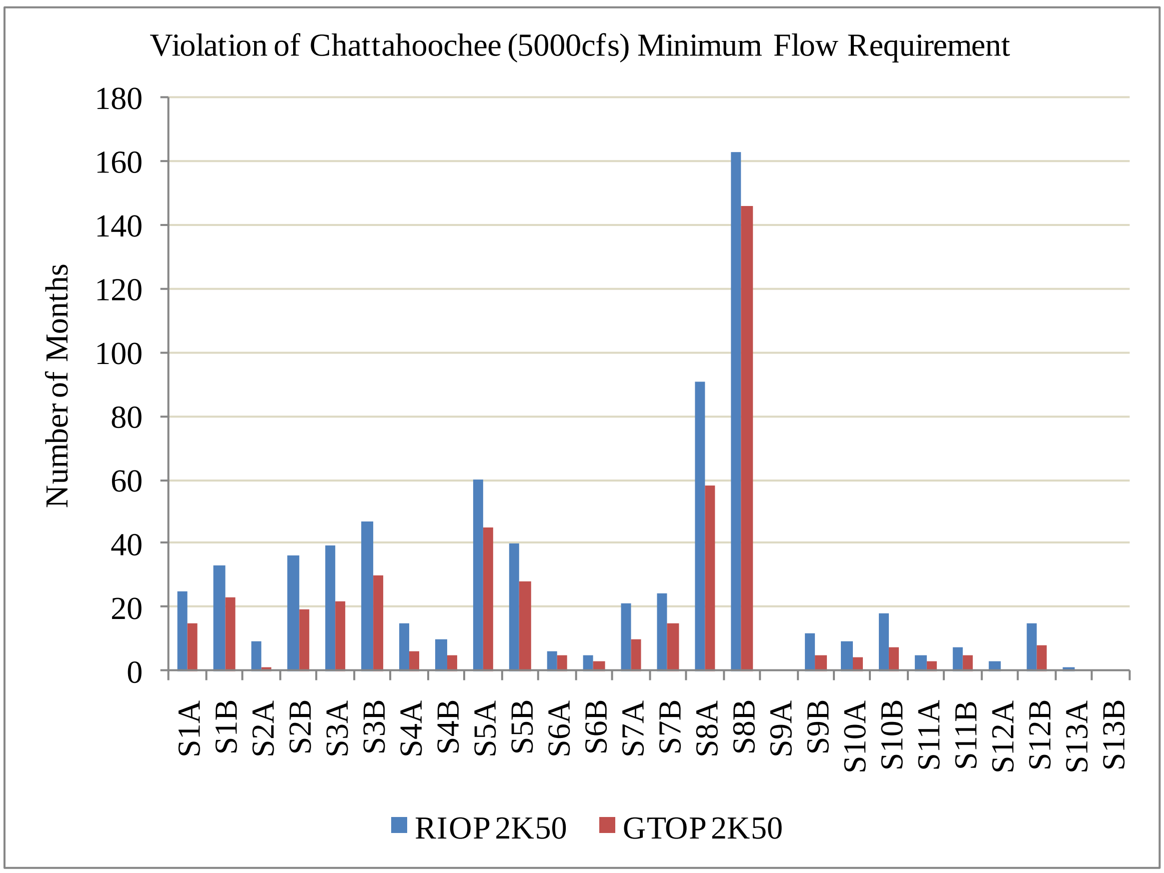


Figure 6.5: Violation of Chattahoochee Minimum Flows (GTOP versus RIOP)

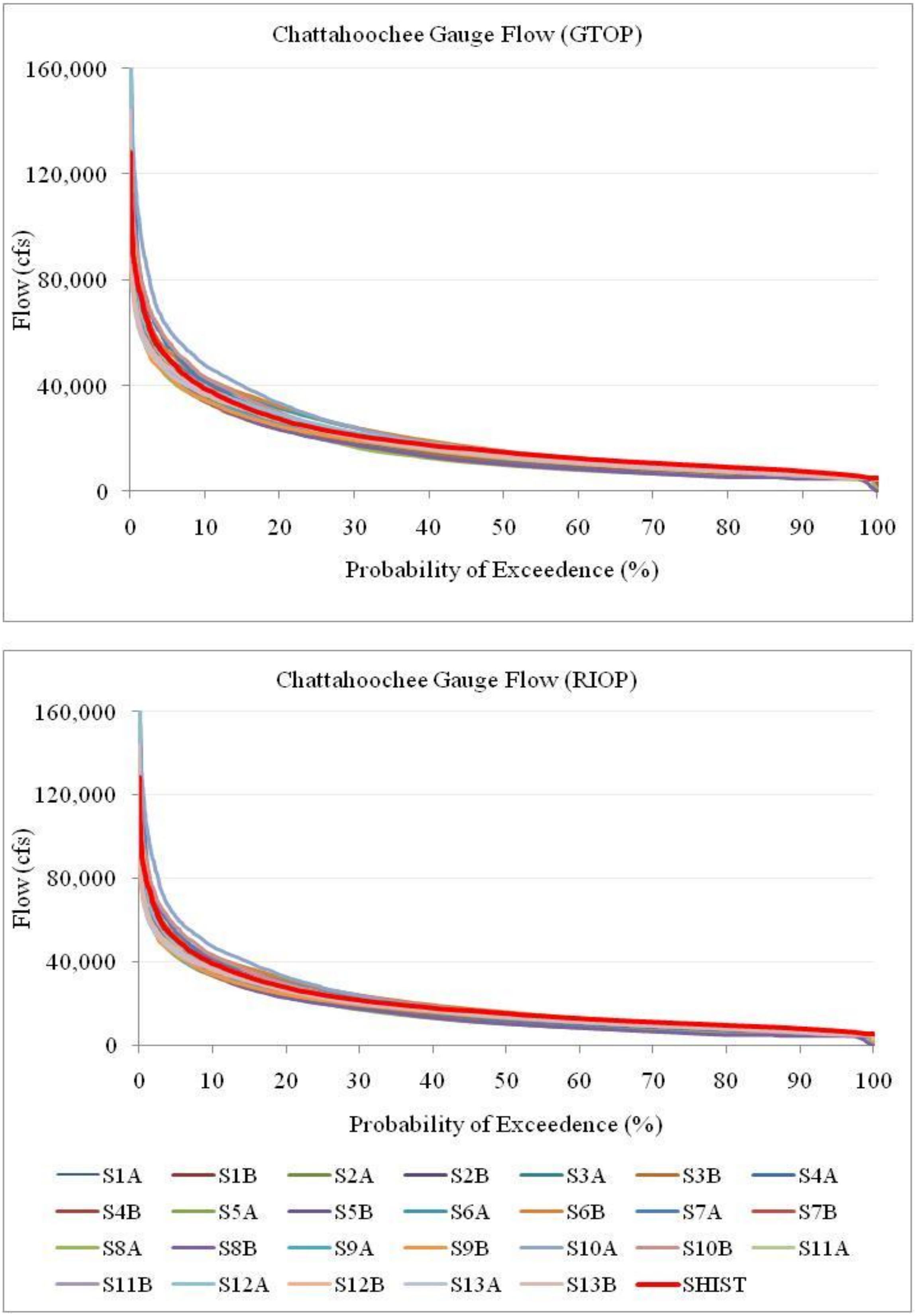


Figure 6.6: Chattahoochee Flow Duration Curves (GTOP versus RIOP)

6.1.2.4 <u>Water Supply Deficits</u>

Figure 6.7 shows the total water supply deficits under the two policies. The water supply deficit is higher under the RIOP in all climate scenarios except the driest. The total deficits range from 0 to 2400 cfs under both policies over the entire assessment horizon, depending on the climate change scenario. Figure 6.7 shows fluctuation in annual deficits most of which occur towards the end of the assessment horizon when demand is greatest.

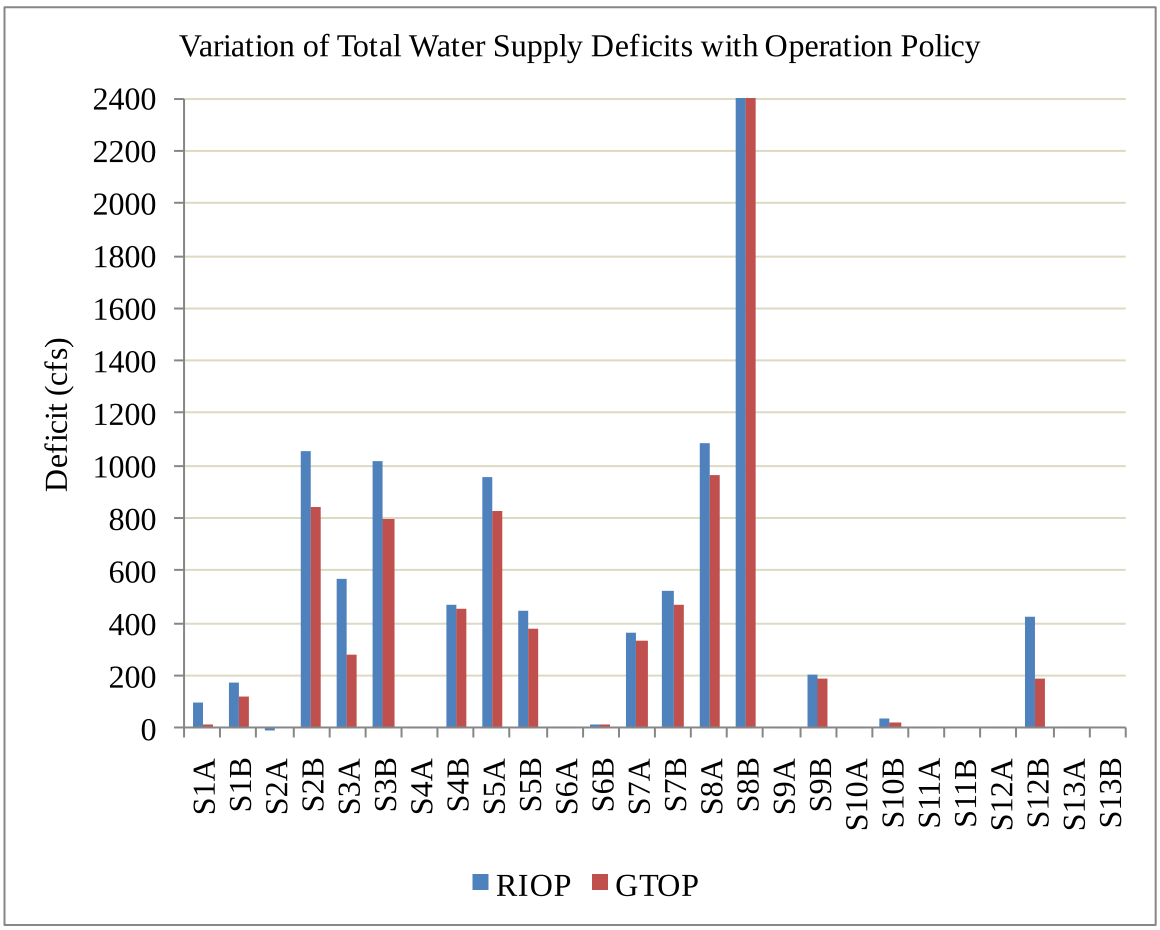
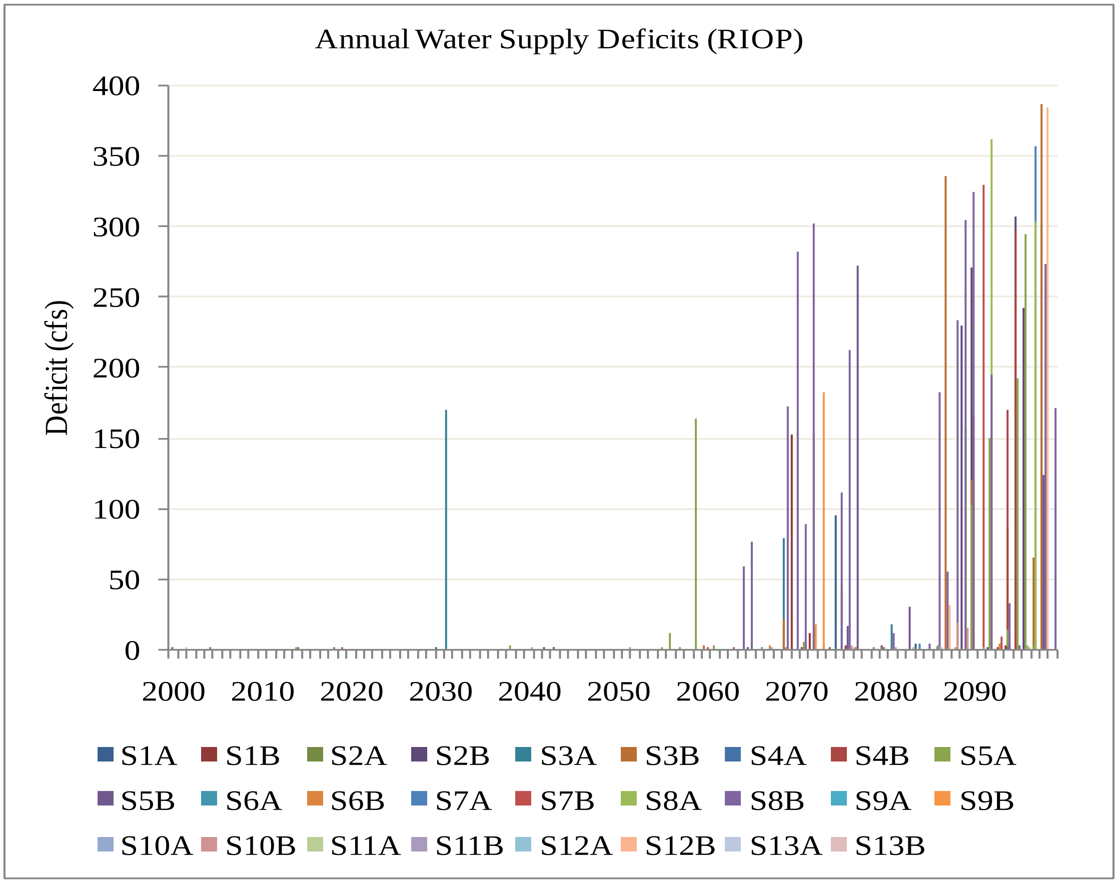


Figure 6.7: Total Water Supply Deficit (GTOP versus RIOP)



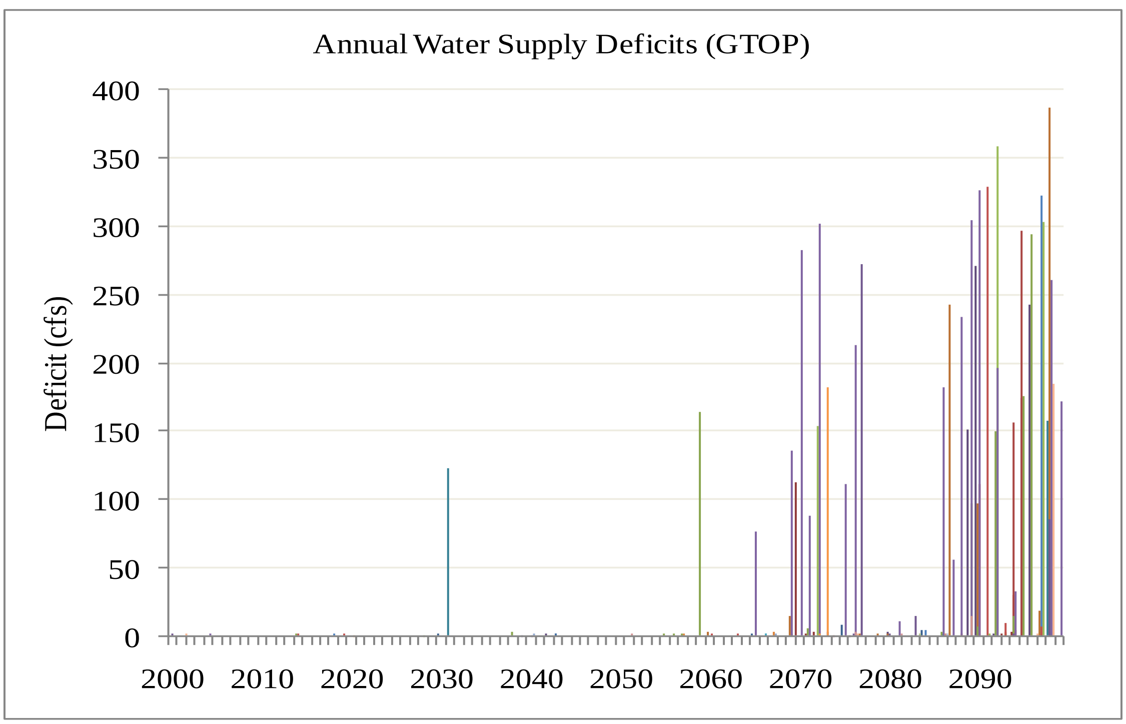


Figure 6.8: Variation of Annual Water Supply Deficit (GTOP versus RIOP)

6.1.3 Assessment of Change in Economic Benefits

6.1.3.1 Recreation Water Use Benefits

Figure 6.9 shows the bounds of incremental annual recreation benefits accruing from implementation of GTOP over RIOP under all climate change scenarios. Recreation benefits under GTOP are higher than those under RIOP most of the time due to the tendency for lake levels to stay higher under GTOP. The incremental annual benefits range from -8 to 96 million dollars depending on the climate change scenario.

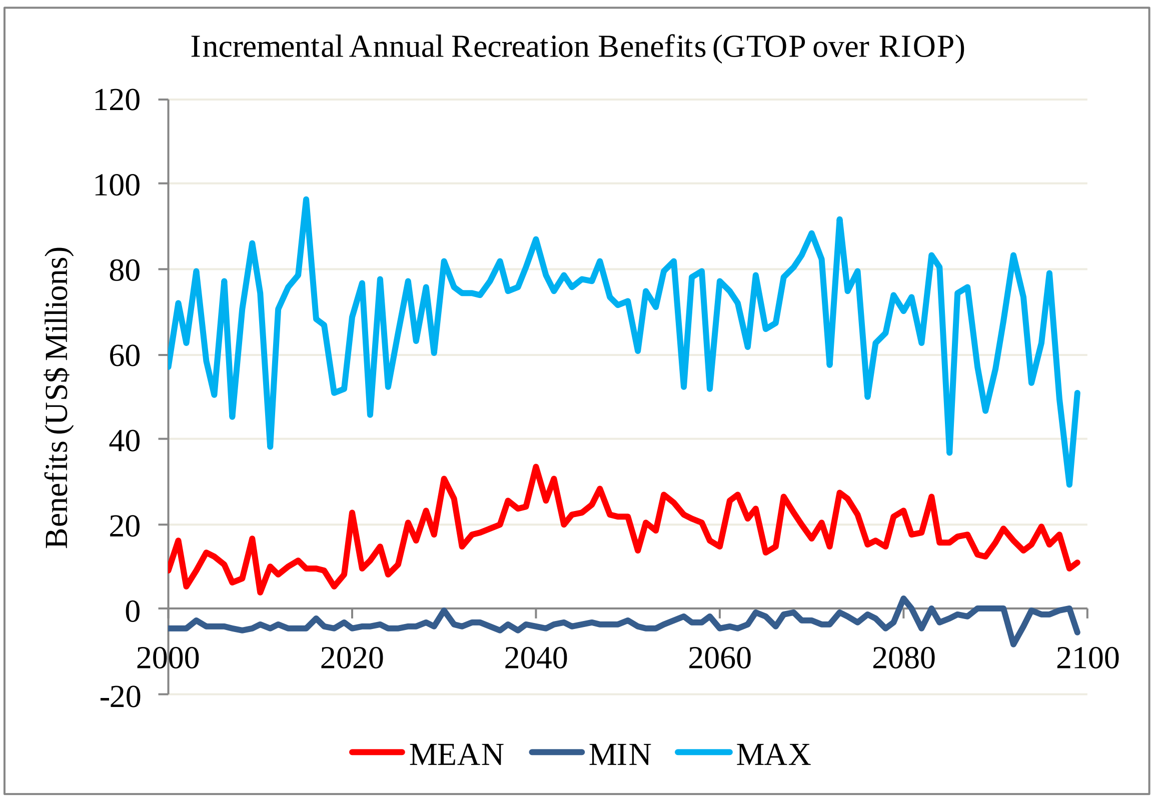


Figure 6.9: Incremental Annual Recreation Benefits (GTOP over RIOP)

6.1.3.2 Hydropower Generation Benefits

Figure 6.10 shows bounds for incremental annual hydropower benefits corresponding to implementation of GTOP instead of RIOP under all climate change scenarios. The difference in benefits switches from positive to negative due to the dependence of hydropower generation on both lake level and discharge. The difference in annual benefits ranges from -8.5 to 7.9 million dollars depending on the climate change scenario.

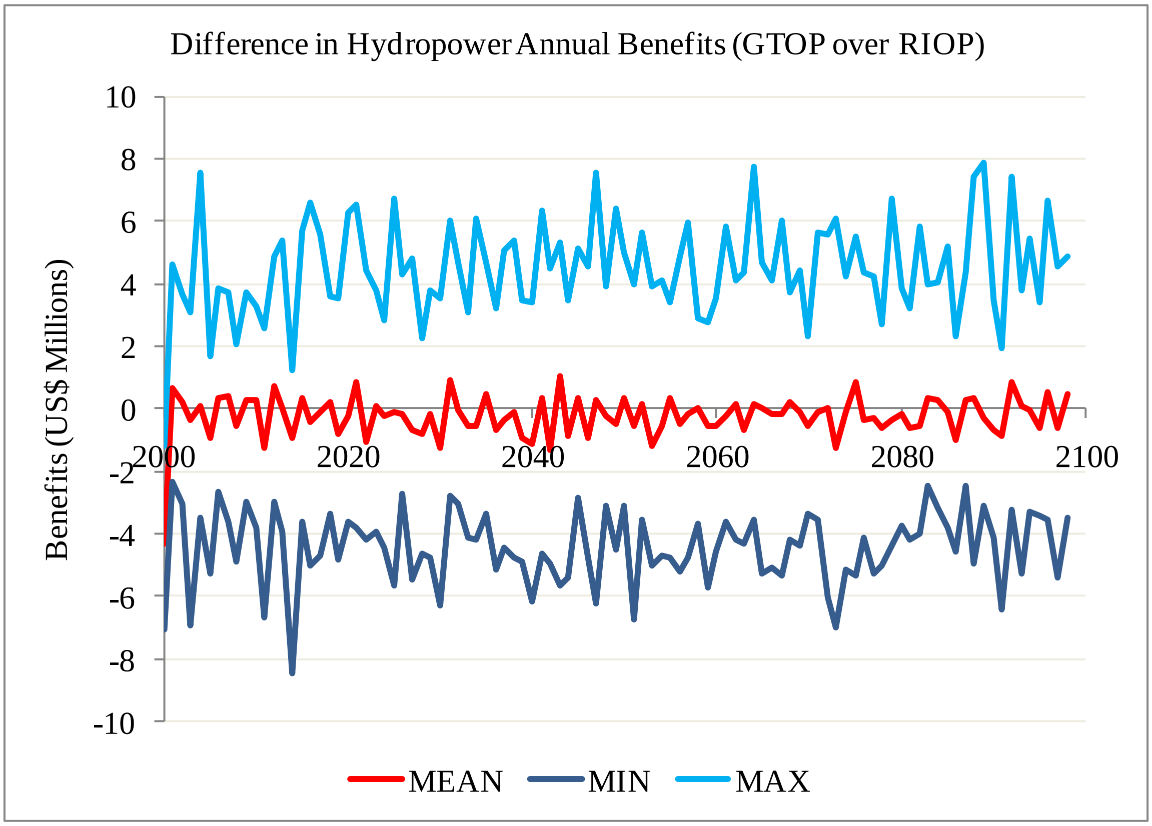


Figure 6.10: Incremental Annual Hydropower Benefits (GTOP over RIOP)

6.1.3.3 Municipal Water Use Benefits

Figure 6.11 shows the incremental annual municipal water supply benefits (measured in terms of consumer surplus). Benefits range from 0 to 67 million dollars depending on the climate scenario. Benefits are attributed to GTOP’s tendency to keep lake levels higher and ability to support increased water supply withdrawals during drought periods. However, because most of the identified savings would be realized during the later years of the assessment horizon, they have lower discounted values and higher uncertainties and should therefore be interpreted as such in any decision making process.

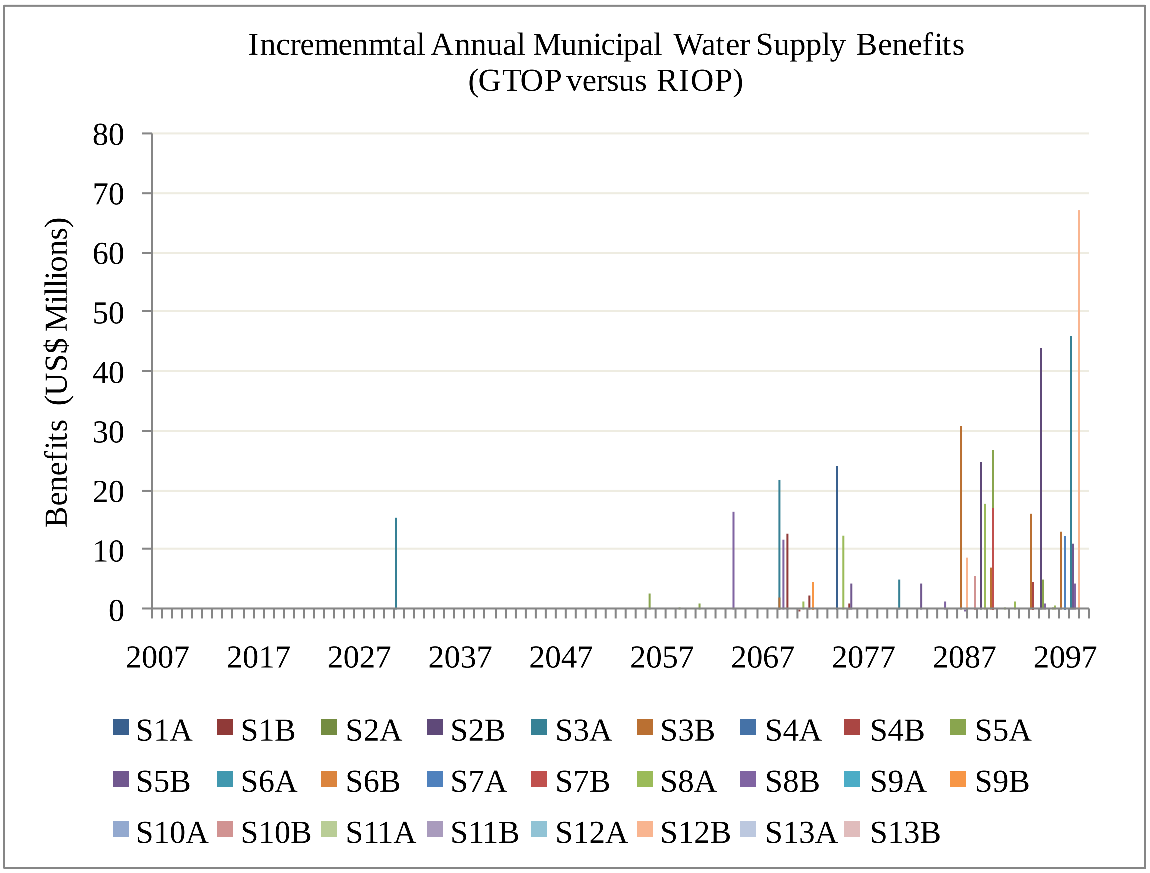


Figure 6.11: Incremental Annual Water Supply Benefits (GTOP versus RIOP)

6.1.3.4 Irrigation Water Use Benefits

There is no change in irrigation benefits corresponding to reservoir operation policy change because all irrigation withdrawals take place in the Flint River sub-basin which has no regulated water storage structures that could potentially be impacted upon by a change in operation policy.

6.1.3.5 Thermal Power Water Use Benefits

There is no change in thermal power benefits because thermal water cooling requirements are satisfied all the time under both policies.

6.1.3.6 Aggregate Water Use Benefits

Figure 6.12 shows bounds of aggregate incremental annual benefits accruing from implementation of GTOP over RIOP under all climate change scenarios. Benefits range between -7 to 93 million dollars depending on the climate change scenario.

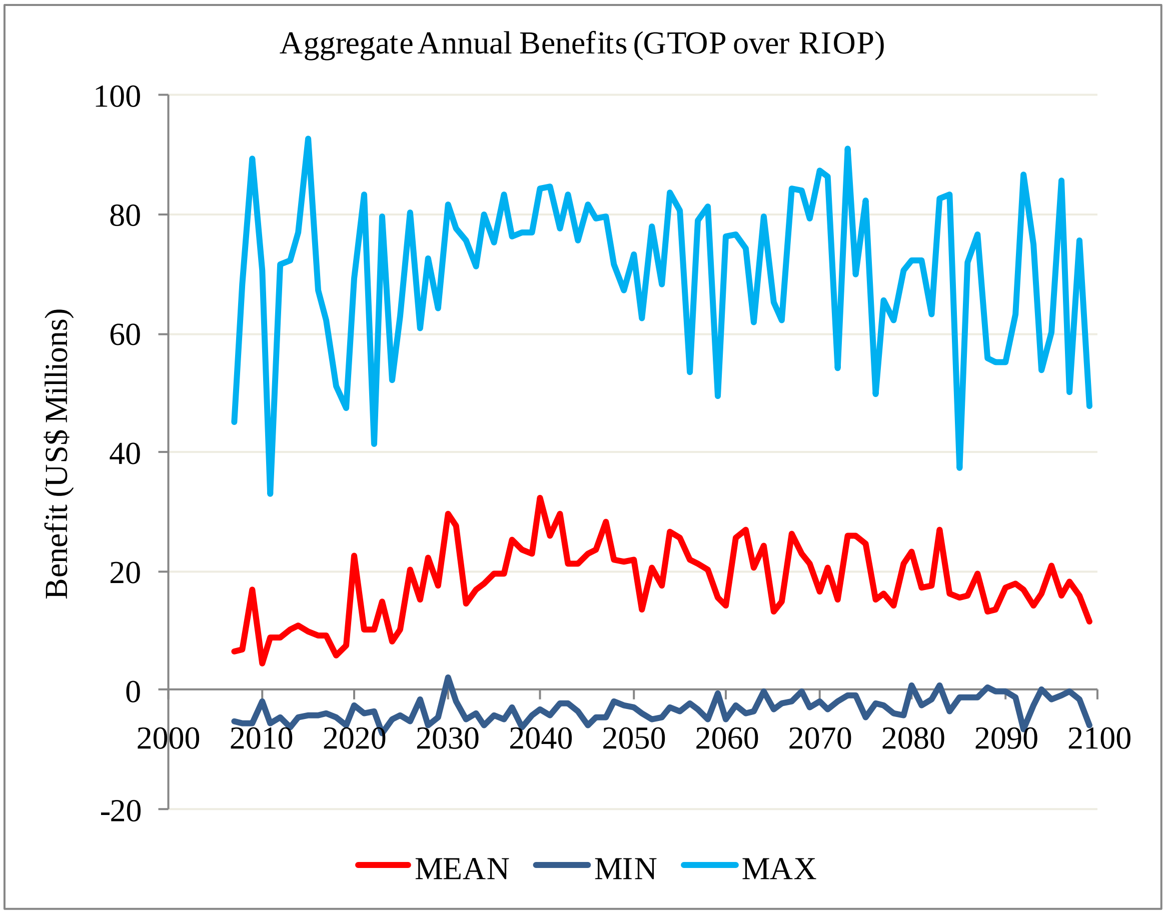


Figure 6.12: Aggregate Incremental Annual Benefits (GTOP versus RIOP)

6.1.4 Summary of Assessment Findings

Based on assessment of the physical and economic performance of the ACF system under GTOP and RIOP, it can be concluded that GTOP is a more efficient reservoir operation policy compared to the existing RIOP. Implementation of GTOP results in incremental aggregate annual benefits 83% of the time under all climate change scenarios. Aggregate annual benefits range between -7 to 93 million dollars with a mean of 18 million. Besides the economic benefits, GTOP also performs better than RIOP in terms of physical outputs, i.e., it results in higher lake levels, less frequency of reservoir depletion and power generation failures, and less violations of minimum flow requirements at critical river sections. GTOP's strength as an adaptive reservoir management policy makes it a technically viable mitigation measure against potential negative impacts of future climate change on the basin's water resources. GTOP implementation would have no financial implications other than those associated with reviewing and amending the existing reservoir operation guidelines, and training of responsible Engineers and Technicians. However, changing the current reservoir operational policy would have legal implications since it was congressionally authorized. There would be need for extensive stakeholder consultations on the proposed changes and an appropriate legal instrument would have to be enacted by Congress to give effect to any proposed revisions to the existing operational policy for reservoirs managed by the Federal government.

6.2 Policy Scenario 2: Variation of Minimum Environment Flow Requirements

Maintenance of adequate water flows for environment conservation and sustainability of aquatic life is one of the key water resources management objectives in the ACF basin. Preservation of healthy ecosystems provides many benefits to basin riparians including abundant fisheries, wildlife habitat, recreation, and clean water. Though it is generally acknowledged that the value of environmental services provided by the basin's aquatic ecosystems is significant, little research has been undertaken to estimate the monetary value of these benefits. Similarly, no attempt has been made to assess the opportunity cost incurred by upstream water users in maintaining the minimum flows. Despite this ambiguity, continued maintenance of the mandatory minimum environment flow requirements at the Chattahoochee gauge (5000cfs) requires that upstream water users forego benefits from using the water for municipal, industrial, and other uses in order for it to be available to meet the downstream minimum flow requirements. Ideally, determination of the appropriate minimum environment flow requirements should have been based on a comprehensive economic evaluation of the opportunity costs foregone by the upstream water users versus the economic benefits derived from downstream environment services. Such an assessment would provide a sound and transparent economic justification for the specified environment flow requirements and would inform stakeholder discussions regarding efficient water allocation in the basin.

This section discusses assessment of benefits/losses that would accrue to the upstream water users if the current environment flow requirements at the Chattahoochee gauge (5000cfs) were relaxed. Estimates of these benefits/losses can give an indication of the opportunity cost incurred by upstream water users in ensuring that specific downstream environment flows are met at the Chattahoochee gauge. The assessment is two fold: (i) Estimation of the impact of changes in the Chattahoochee gauge flow requirements on the system's physical outputs is made, i.e., changes in reservoir levels, energy generation, water supply deficits, and in-stream flow fluctuations; (ii) Economic benefits/losses corresponding to the changes in physical outputs are estimated for each sector and aggregated for all sectors to give an estimate of the opportunity cost foregone by upstream water users. Three minimum flow scenarios are considered corresponding to a reduction in the Chattahoochee flow gauge requirements from 5000 cfs to 4500 cfs, 5000 cfs to 4000 cfs, and an increase from 5000 cfs to 5500 cfs.

6.2.1 Assessment of changes in physical outputs

6.2.1.1 Fluctuation of Reservoir Water Levels

Figure 6.13 shows the frequency of reservoir depletion corresponding to different Chattahoochee gauge flow requirements. The figures show that the higher the environment flow requirements, the higher the likelihood of the reservoirs to be depleted, depending on the climate change scenario. The frequency of Lake Lanier depletion ranges from 0 to 7 months for the 5500 cfs constraint and 0 to 2 months for the 4000 cfs constraint, over the entire assessment period. West Point does not experience any reservoir depletion whereas George and Woodruff follow the same pattern as Lake Lanier. Woodruff experiences depletion under only 3 climate change scenarios compared to 8 for George and 9 for Lake Lanier. Figures 6.14 (a) and (b) show reservoir level fluctuations for Buford and West Point and their corresponding frequency curves. Frequency curves show a significant departure between future lake levels and historical levels at the tail end of the distributions. In this part of the distribution (extreme droughts), the lower Chattahoochee constraint (4500cfs) has more frequency curves above the historical curve than the higher constraints indicating higher levels during drought periods under future climate conditions.

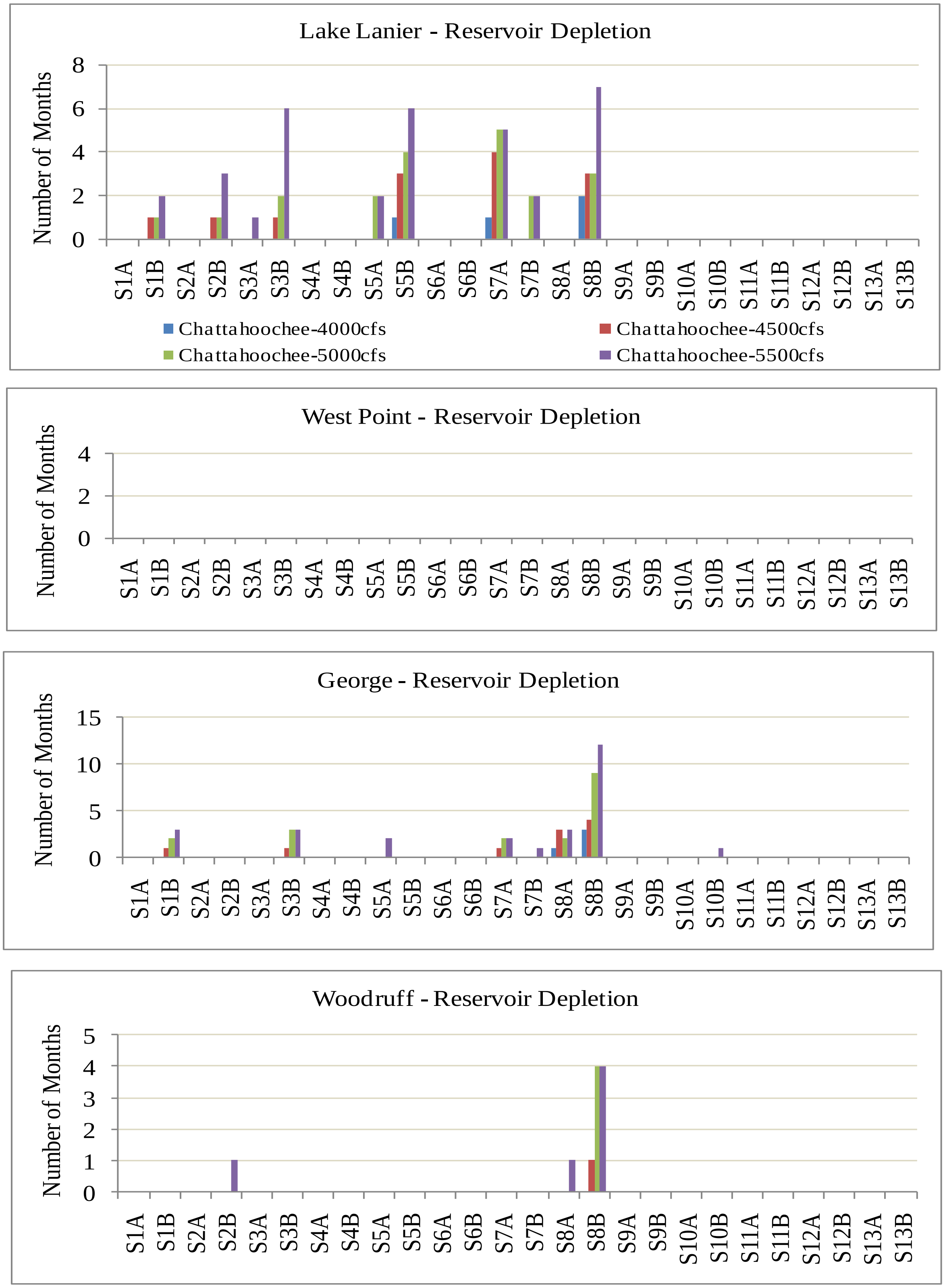


Figure 6.13: Potential Reservoir Depletion under Different Chattahoochee Minimum Flow Requirements

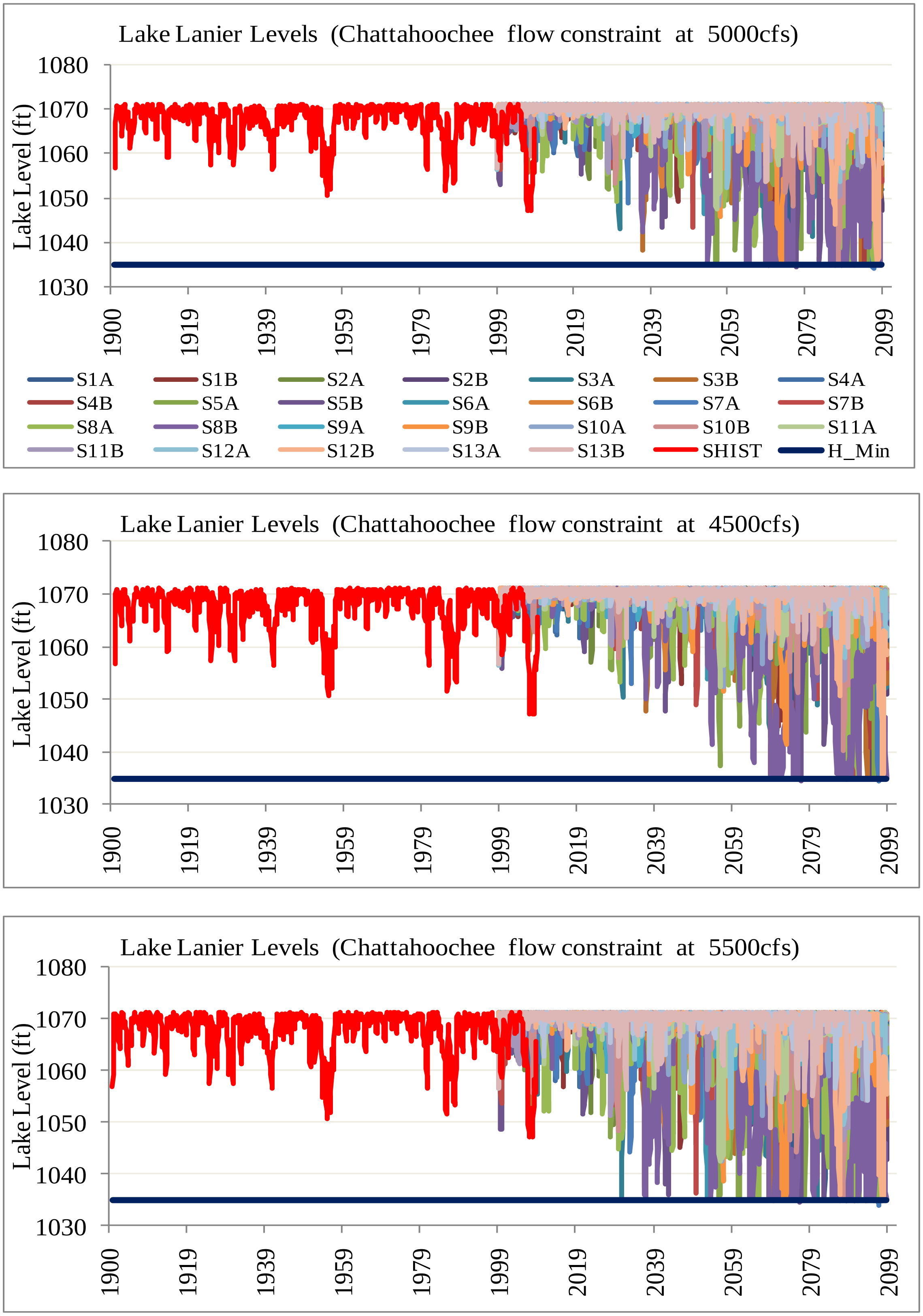
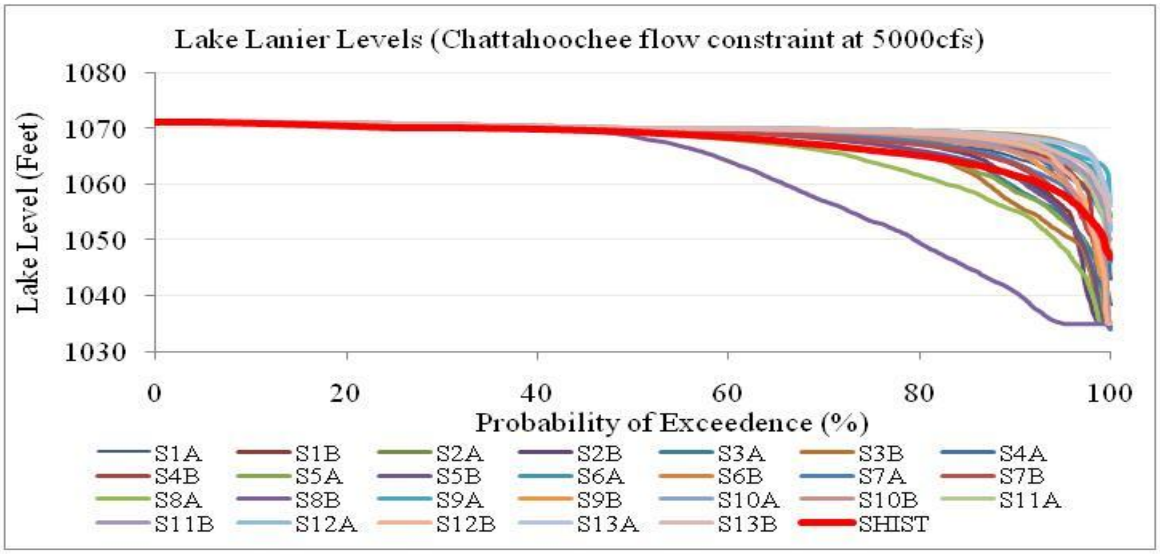
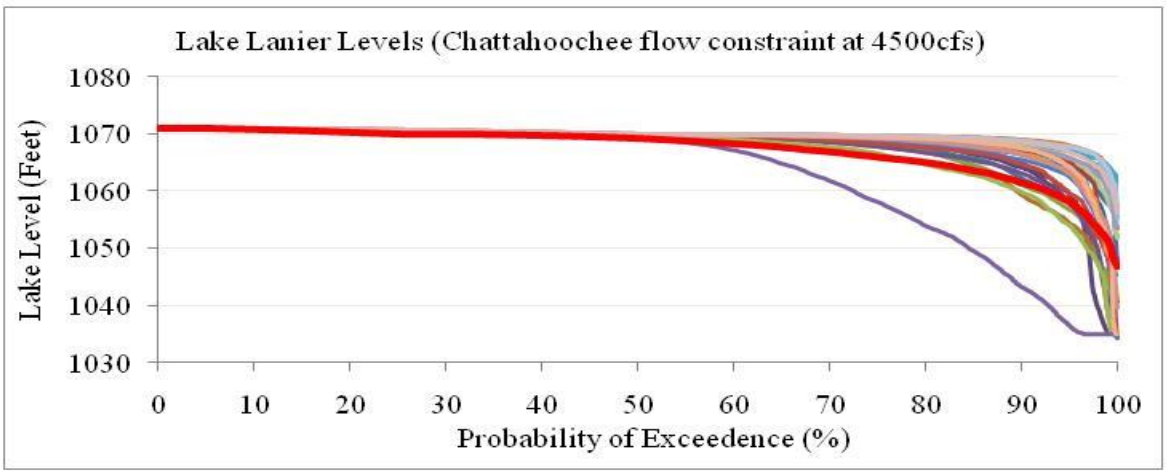


Figure 6.14 (a): Lake Level Fluctuations under Different Chattahoochee Minimum Flow Requirements





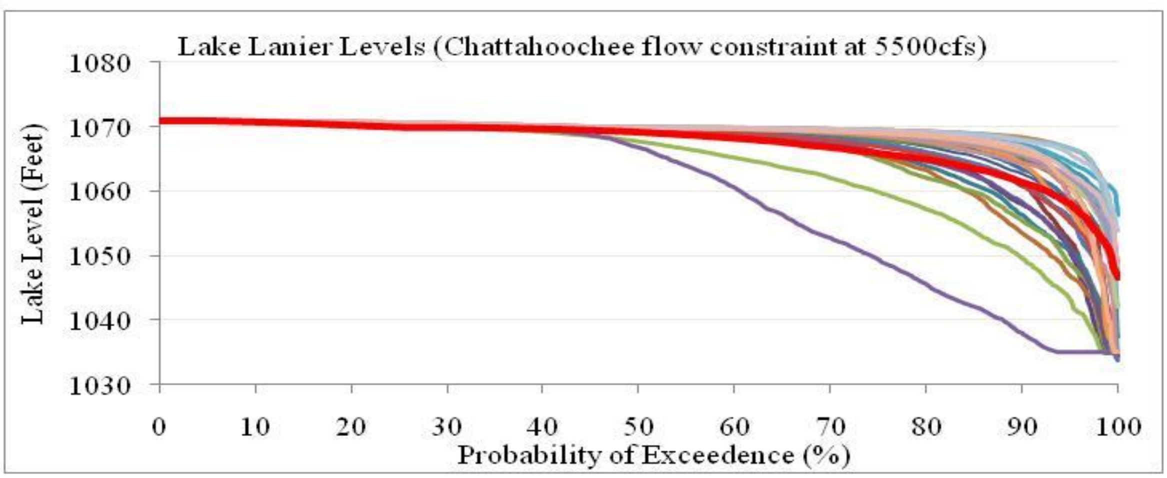


Figure 6.14 (b): Lake Level Duration Curves under Different Chattahoochee Minimum Flow Requirements

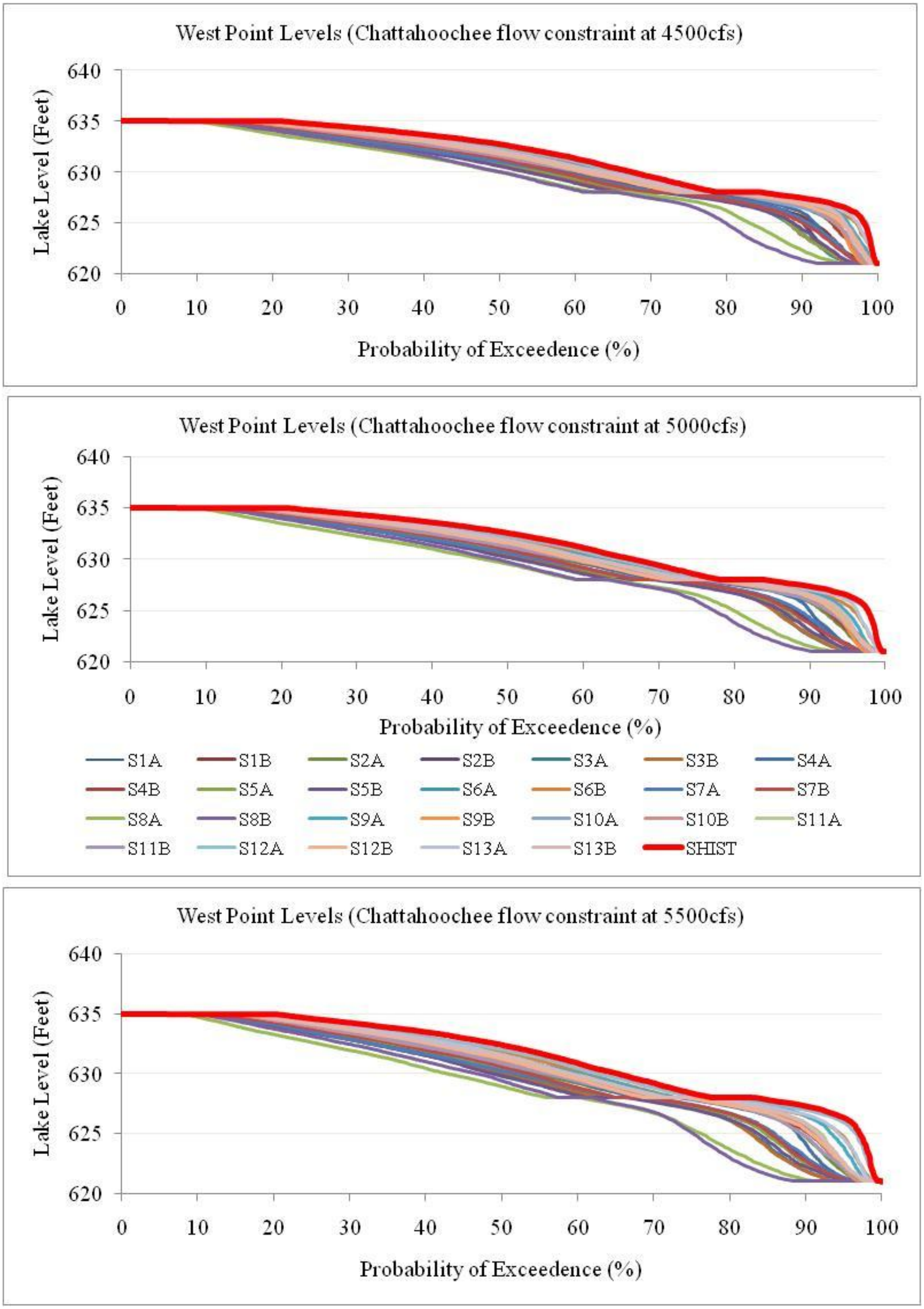


Figure 6.14 (b) continued

6.2.1.2 Variability in Hydropower Generation

Figure 6.15 shows the frequency of hydropower generation failure under different Chattahoochee flow constraints. Buford experiences highest frequency of energy generation failure at highest Chattahoochee flow constraint. The frequency of failure ranges between 0 to 7 months under 5500cfs constraint, 0 to 4 months under 5000cfs, 0 to 3months under 4500cfs, and 0 to 2 months under 4000cfs. The number of climate scenarios registering generation failures increases with the Chattahoochee constraint from 3 scenarios for 4000cfs to 9 scenarios for 5500cfs. West Point does not experience any generation failure while George experiences failure only for 5000cfs and 5500cfs under only 4 climate scenarios. Woodruff registers the highest rate of generation failures of up to 14 months under the driest climate scenario. It experiences generation failure in 24 out the 26 climate scenarios. Figure 6.16 shows Buford and West Point hydropower generation frequency curves under different Chattahoochee flow constraints. There is no significant difference between the different cases in terms of total energy generation.

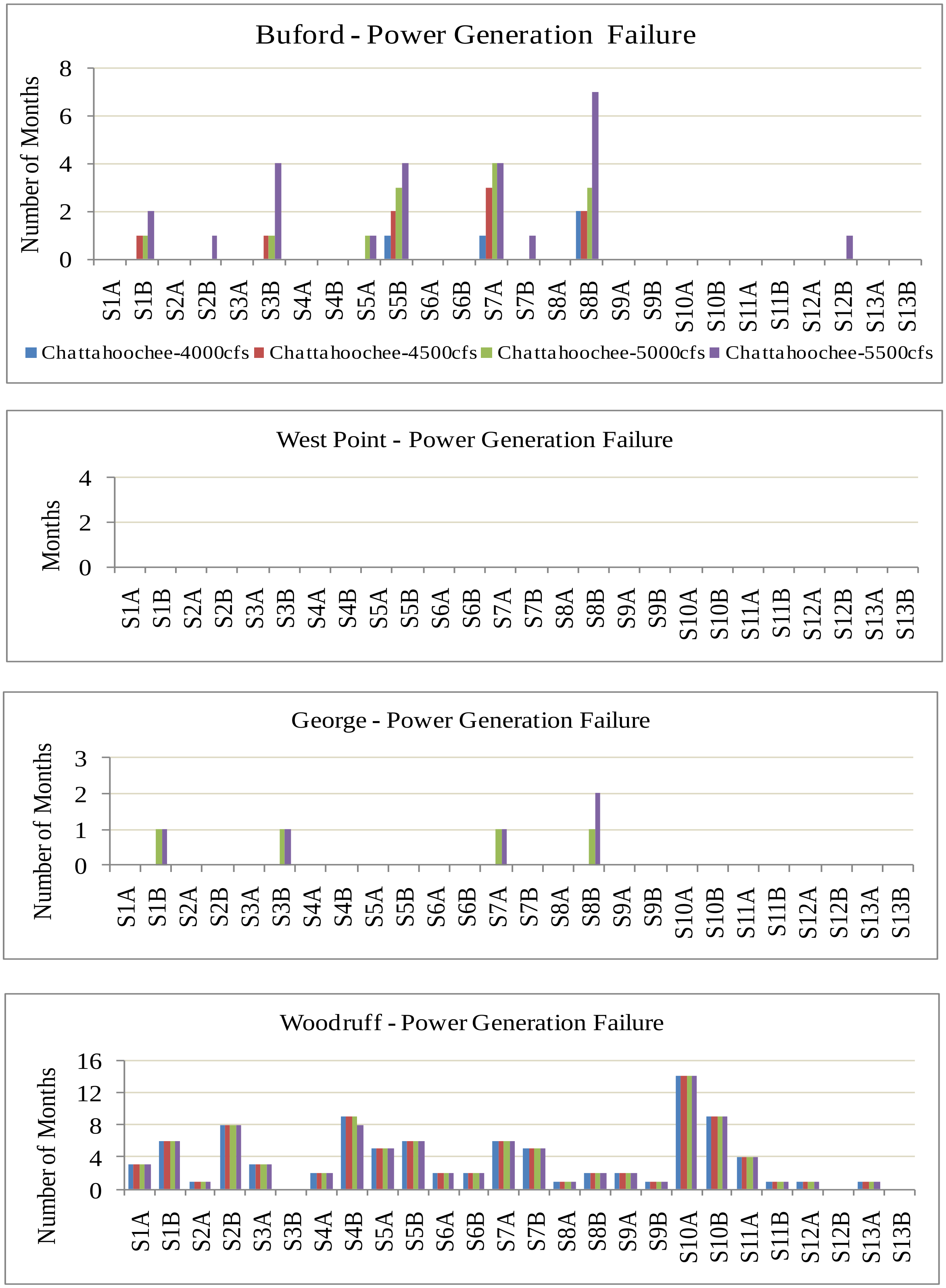


Figure 6.15: Potential Hydropower Generation Failure under Different Chattahoochee Minimum Flow Requirements

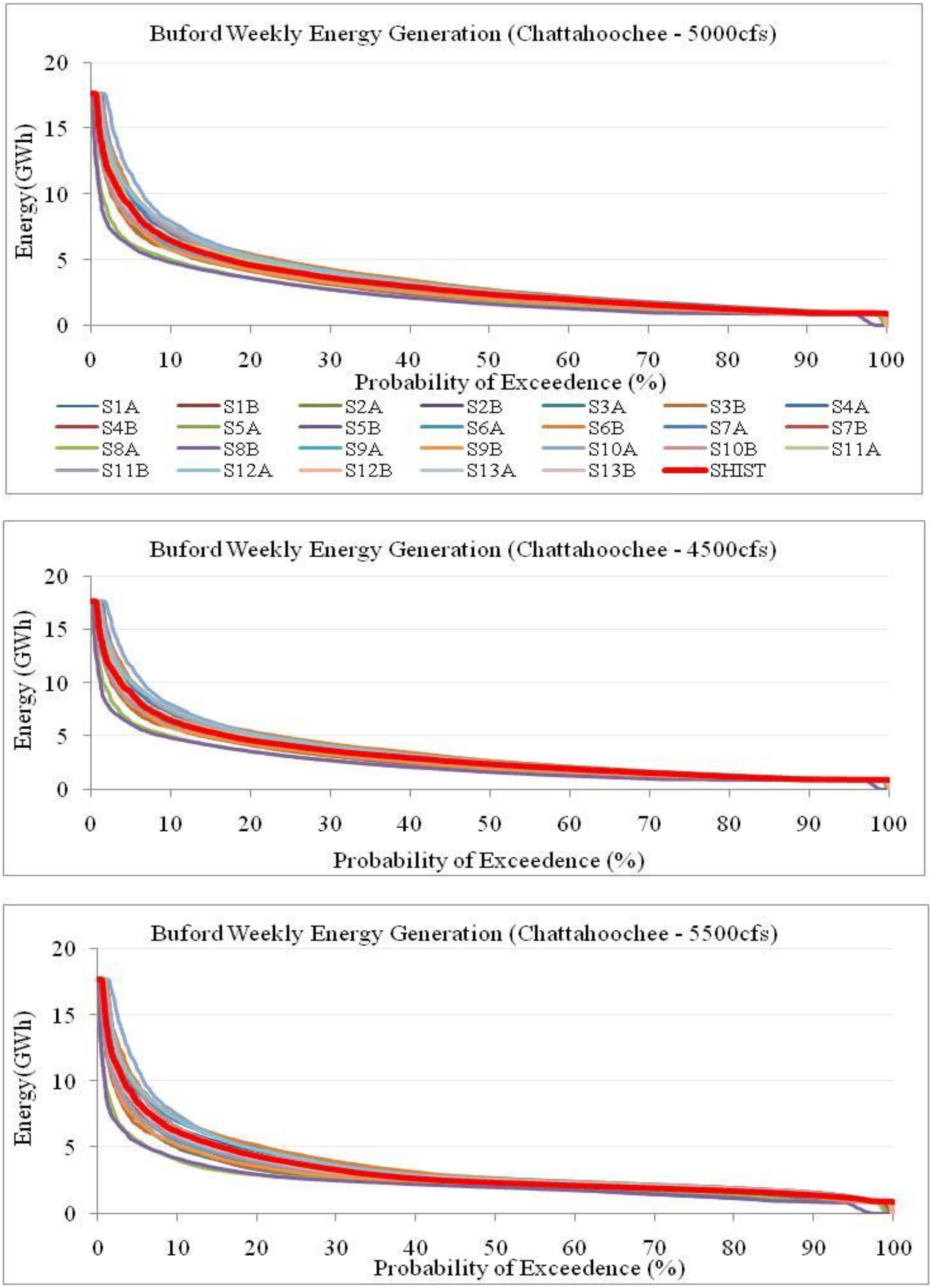


Figure 6.16: Hydropower Generation Duration Curves under Different Chattahoochee Minimum Flow Requirements

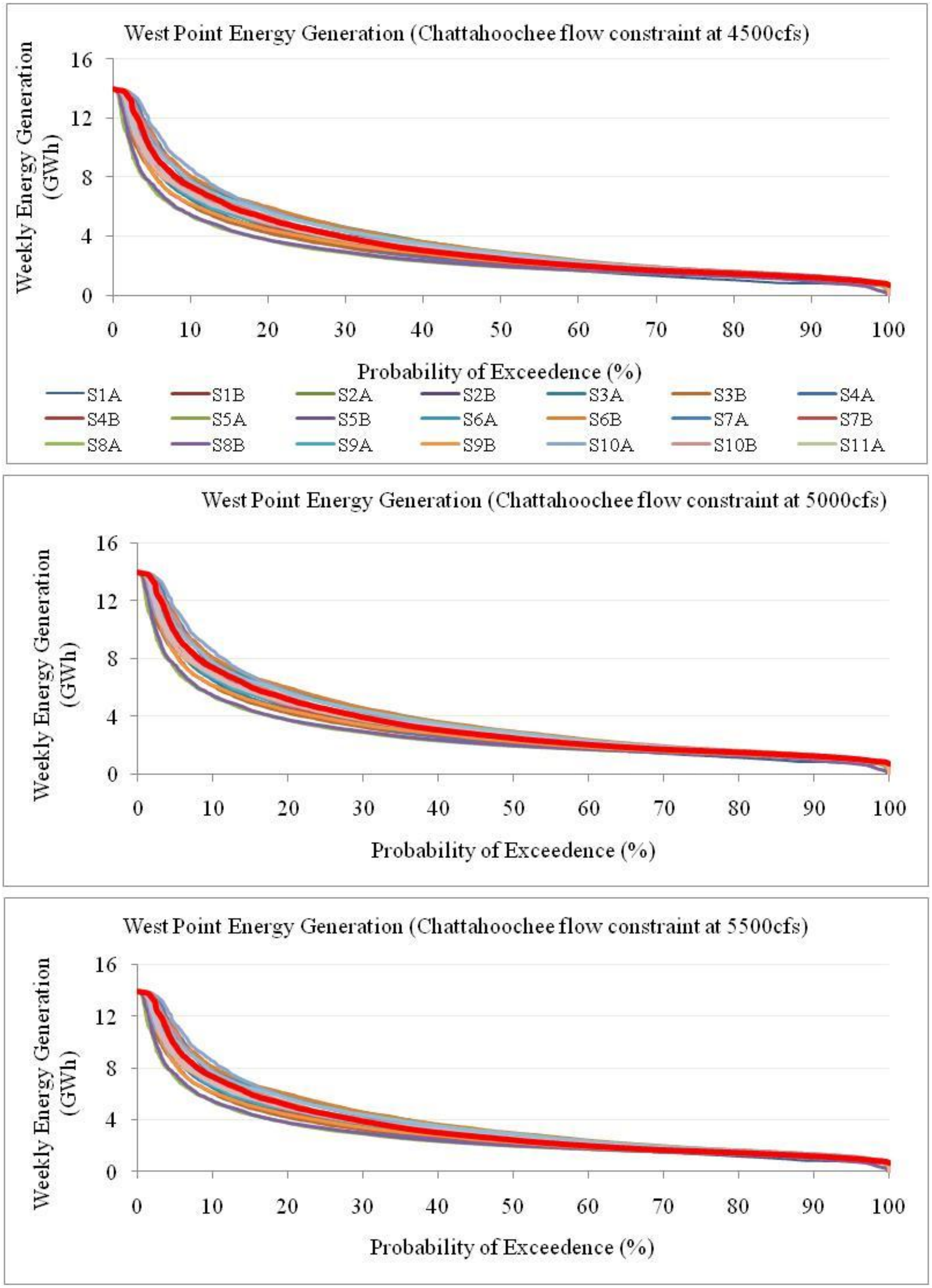


Figure 6.16 continued

6.2.1.3 Water Supply Deficits

Figure 6:17 shows total water supply deficits corresponding to different Chattahoochee gauge flow constraints. The figure shows that the higher the environment flow requirements, the higher the water supply deficits, depending on the climate change scenario. This is because higher environment flow requirements would necessitate reductions in upstream water supply abstractions resulting in increased water supply deficits. Under the driest scenario (S8B), the basin-wide annual total water supply deficit ranges from about 1335cfs to about 2320cfs, for the 4000cfs and 5500cfs respectively. Deficits are experienced in 16 out of the 26 climate change scenarios. Figure 6.18 shows variability in annual municipal water supply deficit over the entire assessment period, with most deficits occurring during the later years due to significant increase in water demand.

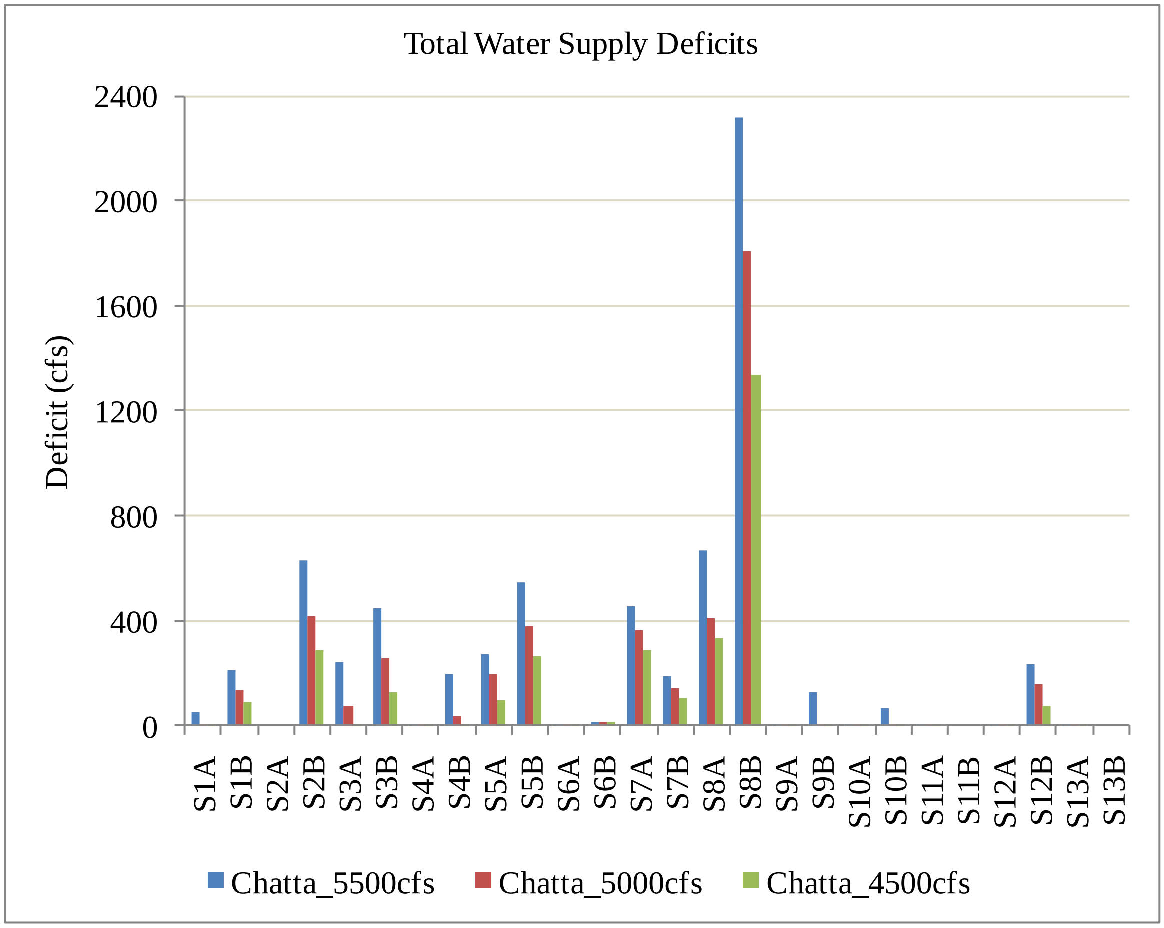
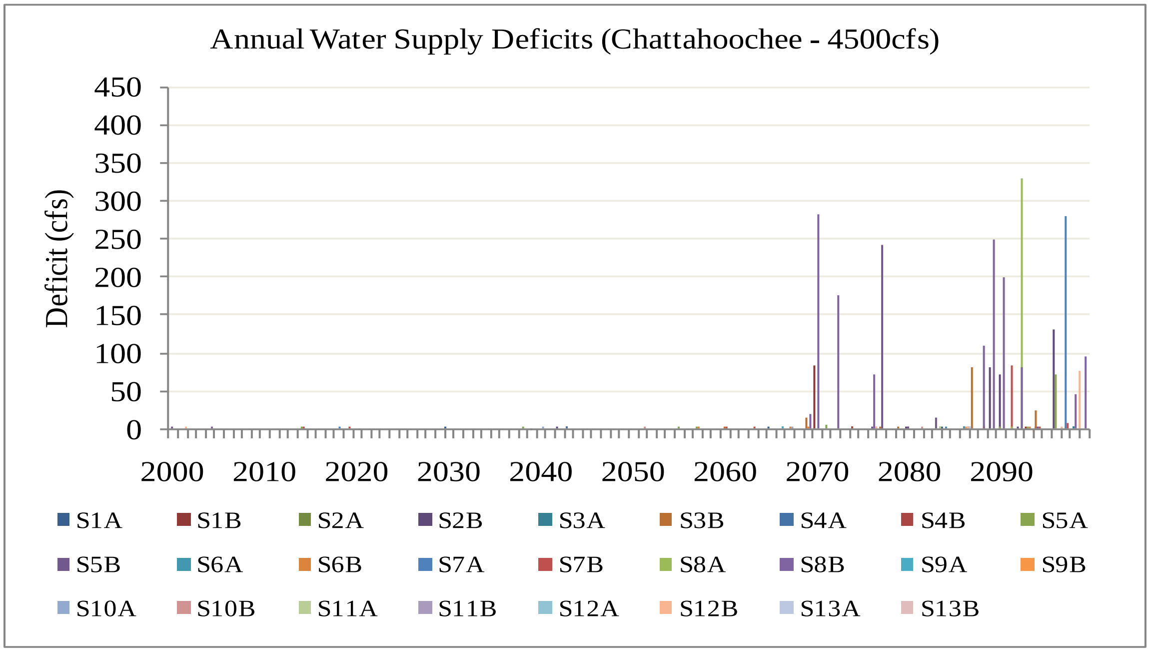
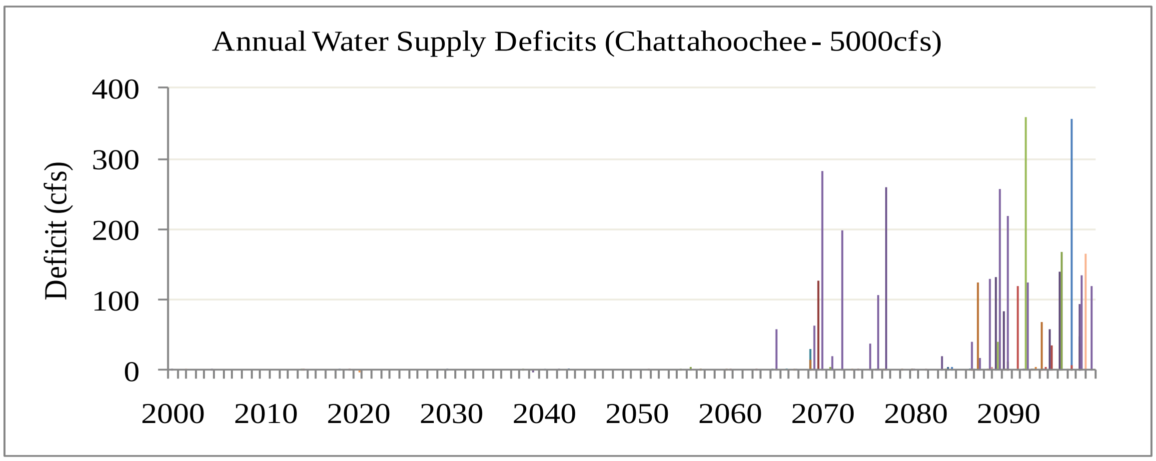


Figure 6.17: Total Water Supply Deficit under Different Chattahoochee Minimum Flow Requirements





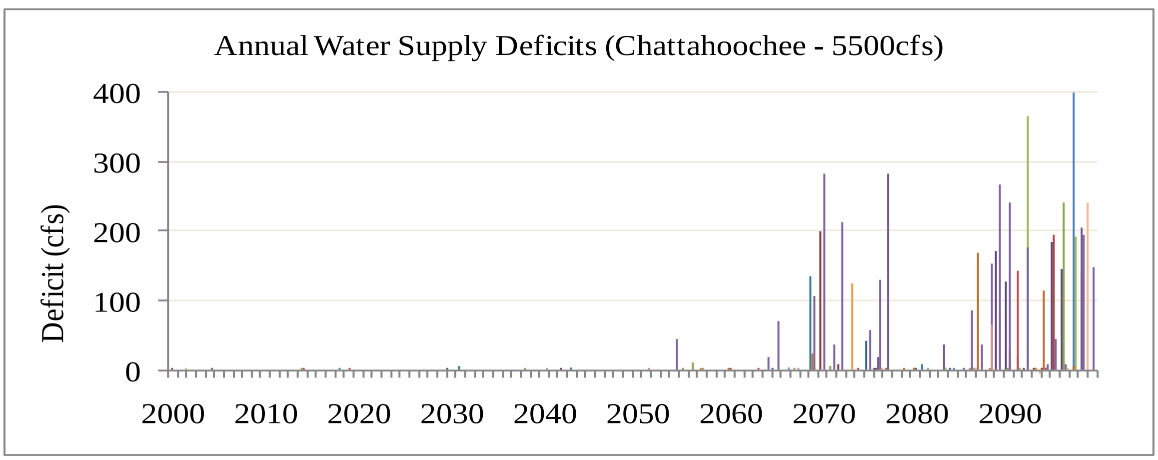


Figure 6.18: Annual Water Supply Deficit under Different Chattahoochee Minimum Flow Requirements

6.2.2 Assessment of Opportunity Costs

6.2.2.1 Municipal Water Use Opportunity Costs

Figure 6.19 shows the economic loss (measured in terms of loss of consumer surplus) that would be incurred by upstream municipal water users to ensure maintenance of different levels of downstream environment flow requirements. The figure shows that the higher the environmental flow requirements, the higher the loss that would be incurred as a result of increased water supply deficits. The additional economic loss corresponding to an increase in the Chattahoochee environmental flow constraint from 5000cfs to 5500cfs ranges from 0 to 110 million dollars annually depending on the future climate change scenario. The highest losses correspond to the drier climate change scenarios that are associated with highest water supply deficits. On the contrary, relaxing the constraint from 5000cfs to 4500cfs would result in gains of up to 120 million dollars. Relaxing the constraint further to 4000cfs would not result in any additional savings. Most of the savings would be realized during the later years of the assessment horizon when municipal water demands are expected to be highest.

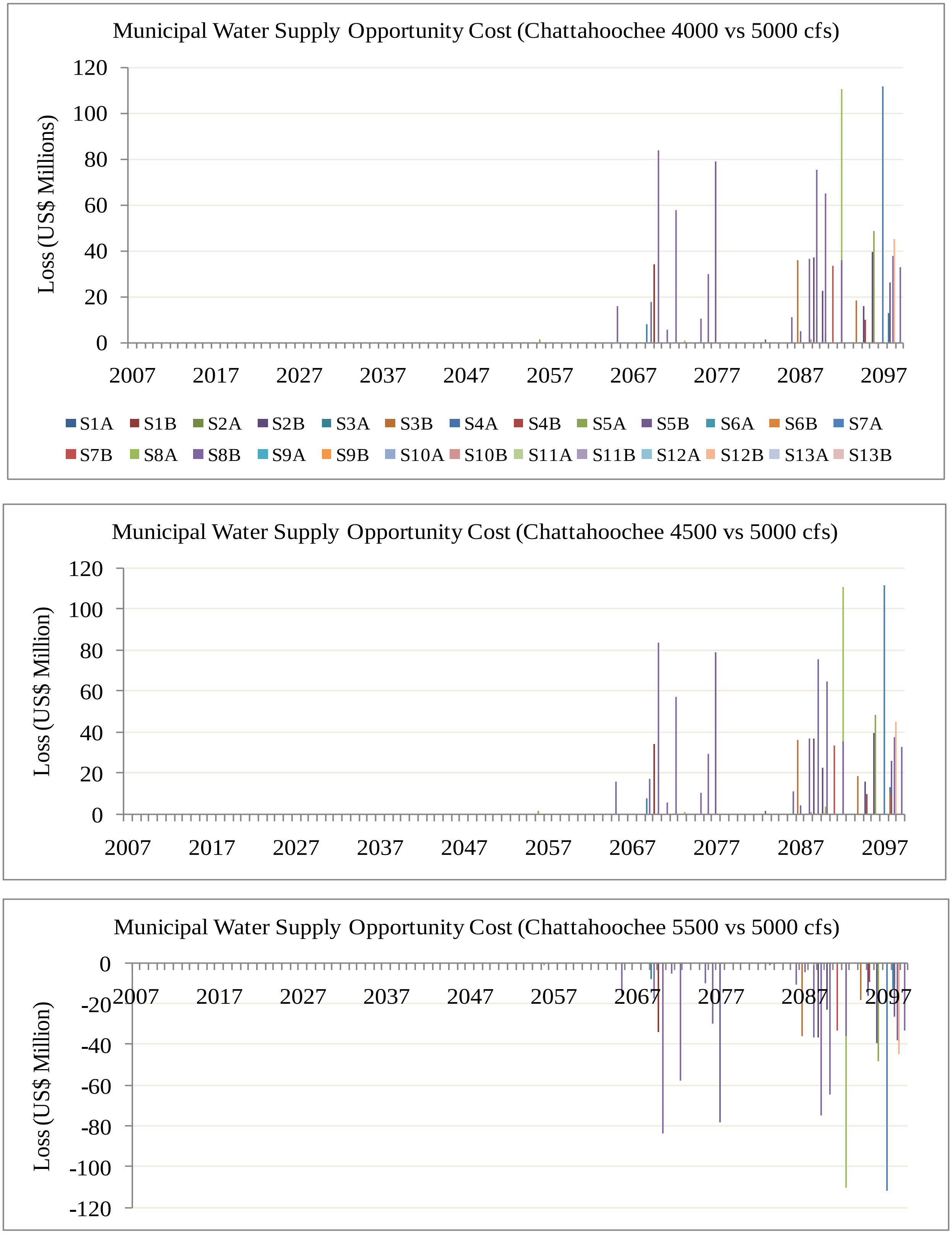


Figure 6.19: Municipal Water Supply Annual Opportunity Cost under Different Chattahoochee Minimum Flow Requirements

6.2.2.2 <u>Hydropower Generation Opportunity Costs</u>

Figure 6.20 shows bounds for annual hydropower benefits foregone to ensure maintenance of different levels of environment flow requirements downstream as represented by different Chattahoochee gauge flow constraints. The figure shows that for a particular scenario (say 4000cfs versus 5000cfs) there is no distinct relationship between opportunity cost and Chattahoochee gauge flow constraint because of the complex nature of energy generation which depends on both discharge and lake level. For example, whereas a higher environmental flow constraint would necessitate higher releases from the reservoirs, this would not necessarily translate into higher energy generation since lake levels would tend to be lower in that case. Similarly, for the case in which the constraint is lower, though the reservoir levels tend to be higher, the discharges required to meet lower environment flow requirements are much lower. Across scenarios, the lower the flow constraint, the wider the range of benefits/losses. If the Chattahoochee flow constraint is reduced from 5000cfs to 4000cfs, the corresponding net benefits range between -10 to 17.6 million dollars depending on the climate change scenario. However, if the constraint is reduced from 5000 to 4500cfs, the range narrows down to -5 to 13 million dollars. An increase in the constraint from 5000cfs to 5500cfs would result in net hydropower benefits ranging between -10 and 5.5 million dollars.

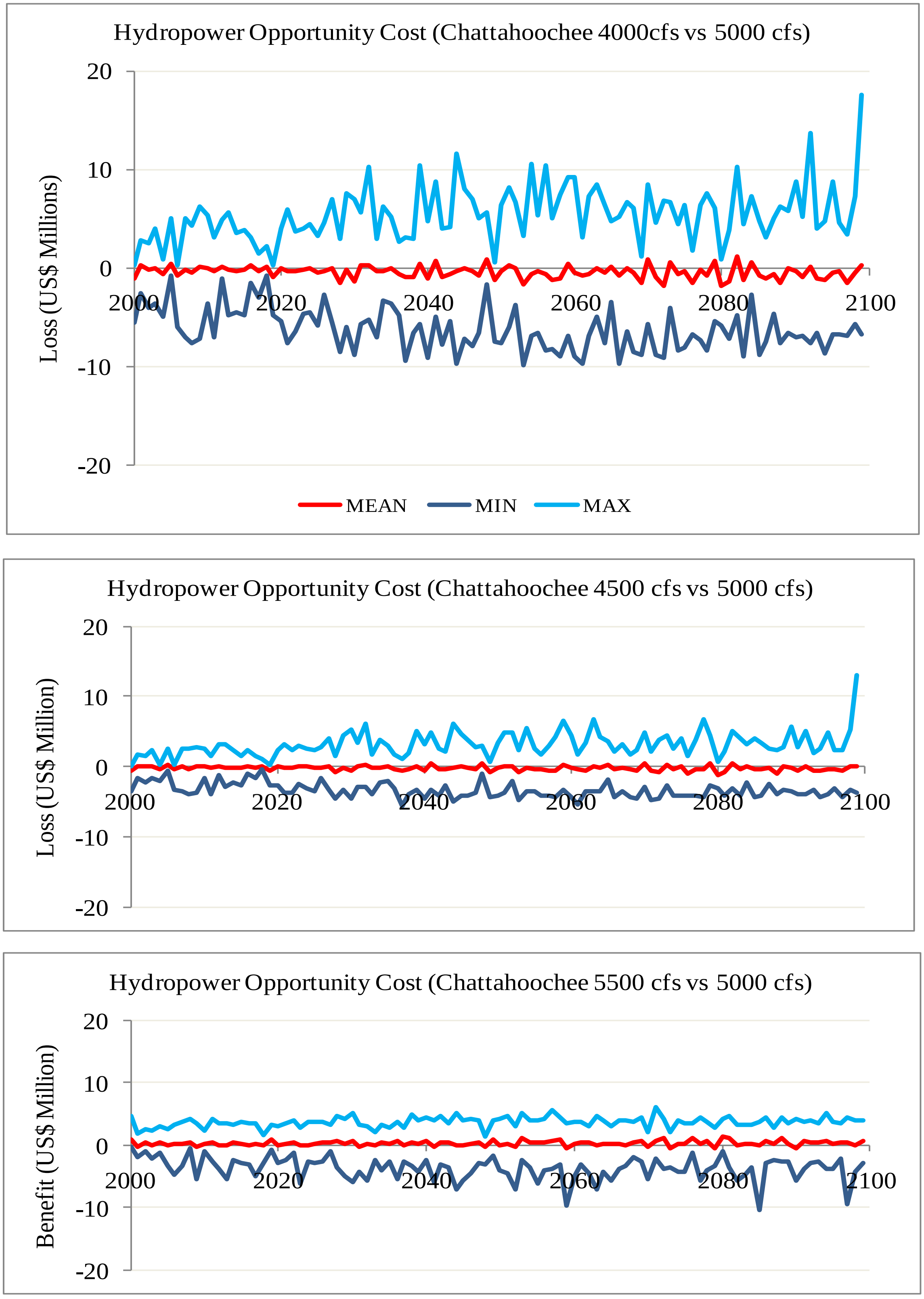
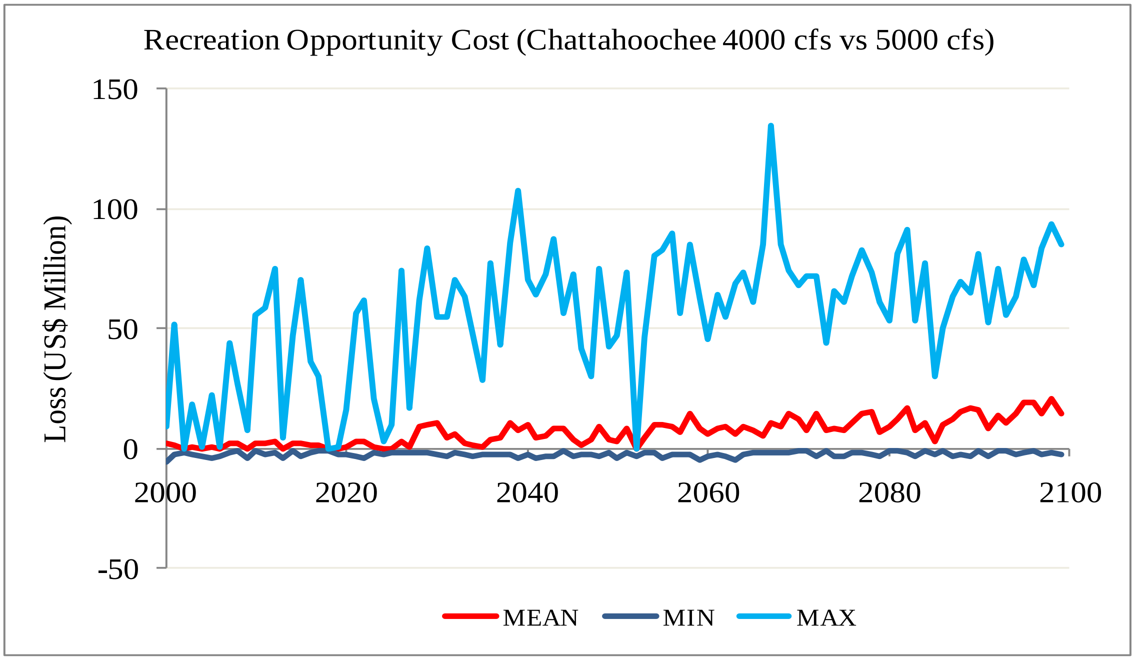
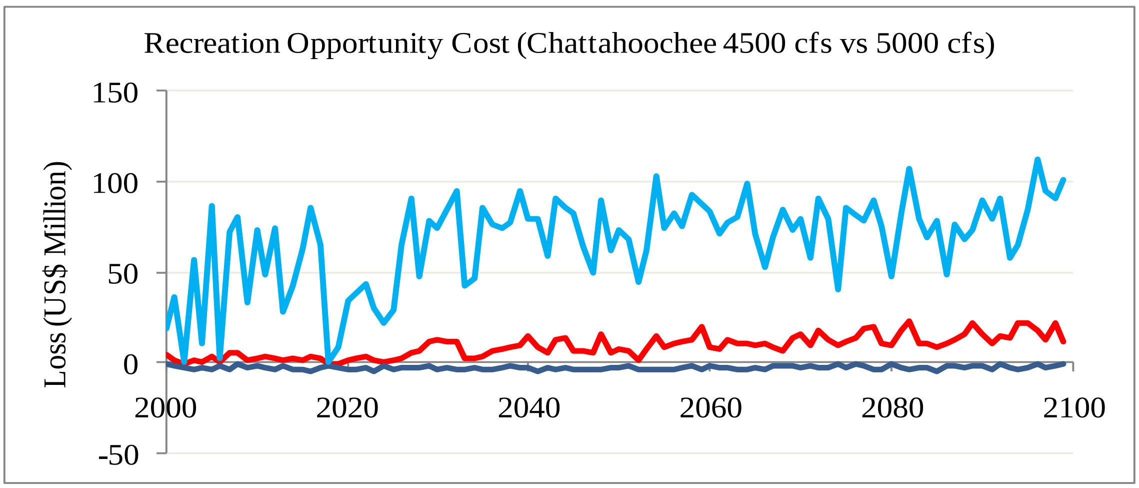


Figure 6.20: Annual Hydropower Opportunity Costs under Different Chattahoochee Minimum Flow Requirements

6.2.2.3 Recreation Water Use Opportunity Costs

Figure 6.21 shows bounds for annual recreation benefits foregone by upstream water users to ensure maintenance of different levels of downstream environment flow requirements. The figure shows that the higher the environmental flow requirements, the higher the recreation benefits foregone by upstream water users. If the constraint is increased from 5000 to 5500cfs, upstream water users would forego recreational benefits of up to 80 million dollars annually. The additional recreation benefits that would accrue to upstream water users if the flow constraint was decreased from 5000cfs to 4500cfs range from 0 to 113 million dollars depending on the future climate change scenario. The highest benefits correspond to the drier climate scenarios. The same trend is observed when the constraint is relaxed further to 4000cfs with the benefits increasing to 135 million dollars.





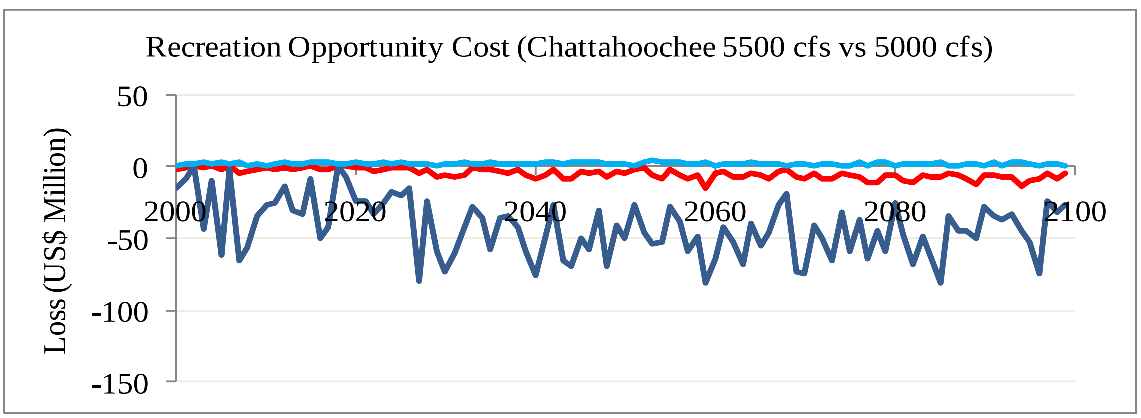


Figure 6.21: Recreation Annual Opportunity Costs under Different Chattahoochee Minimum Flow Requirements

6.2.2.4 Irrigation Water Use Opportunity Costs

Figure 6.22 shows additional irrigation costs that would be incurred by upstream farmers to ensure maintenance of different levels of downstream environment flow requirements. The figure shows that the higher the environmental flow requirements, the higher the additional irrigation water supply costs that would be incurred by upstream water users to meet the corresponding irrigation deficit. The additional irrigation water supply costs that would be incurred by upstream water users if the Chattahoochee flow constraint increases from 5000cfs to 5500cfs range from 0 to 0.11 million dollars annually depending on the future climate change scenario. On the contrary, relaxing the constraint from 5000cfs to 4500cfs would result in savings of up to 0.1 million dollars. Relaxing the constraint further to 4000cfs would not result in any additional cost savings for the farmers.

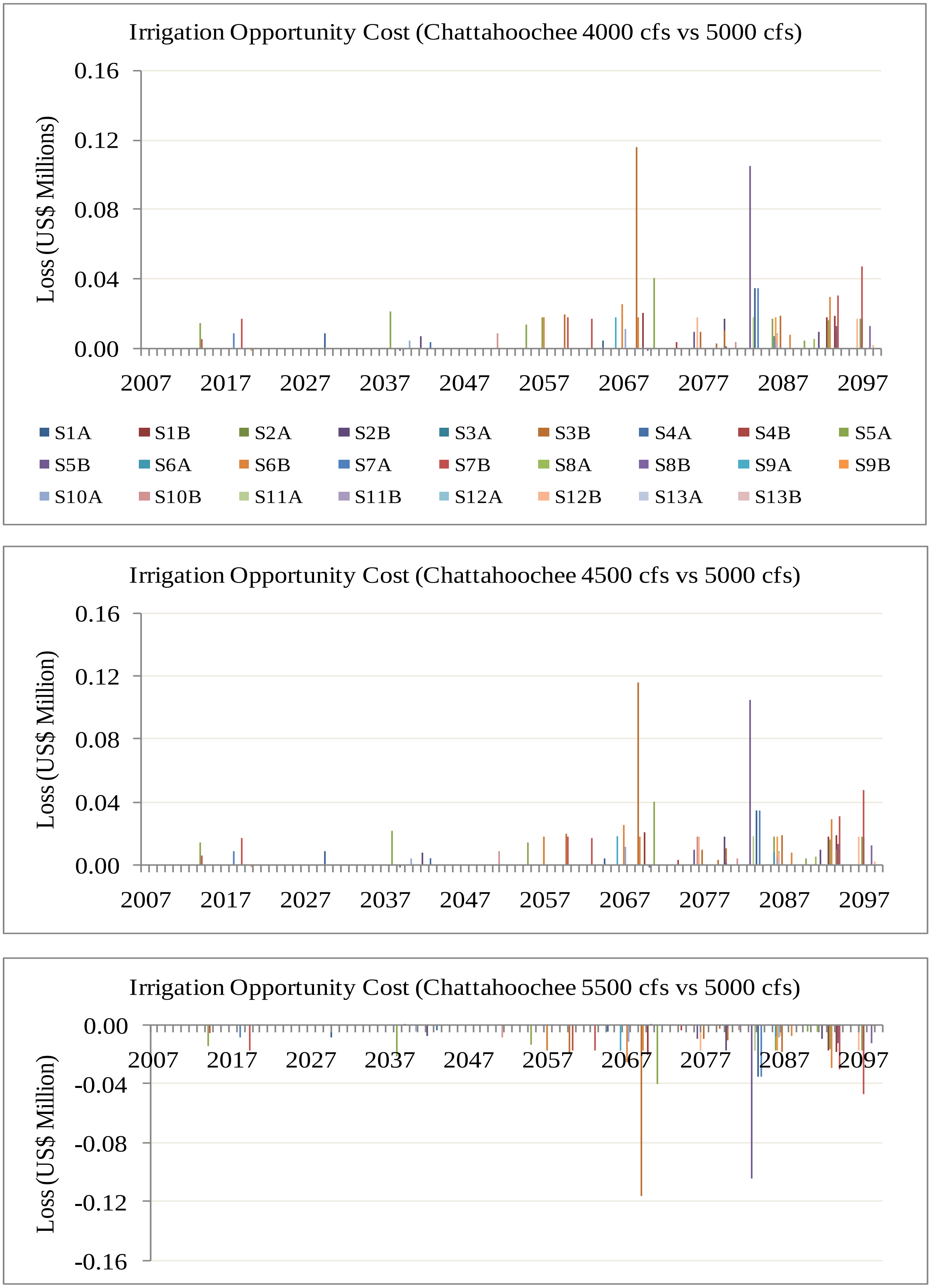


Figure 6.22: Irrigation Annual Opportunity Costs under Different Chattahoochee Minimum Flow Requirements

6.2.2.5 Thermal Power Water Use Benefits

No Thermal Power opportunity costs are incurred because thermal water cooling requirements are satisfied all the time under all Chattahoochee constraints.

6.2.2.6 Aggregate Opportunity Costs

Figure 6.23 shows bounds for aggregate net economic benefits foregone by upstream water users to ensure maintenance of different levels of downstream environment flow requirements. The figure shows that the higher the environmental flow requirements, the higher the benefits foregone by upstream water users. The aggregate opportunity cost that would be incurred by upstream water users if the Chattahoochee environmental flow constraint increases from 5000 cfs to 5500 cfs range between 0 and 91 million dollars annually depending on the future climate change scenario. On the contrary, relaxing the constraint from 5000 cfs to 4500 cfs would result in savings of up to 101 million dollars. Relaxing the constraint further to 4000 cfs would result in savings of up to 135 million dollars annually.

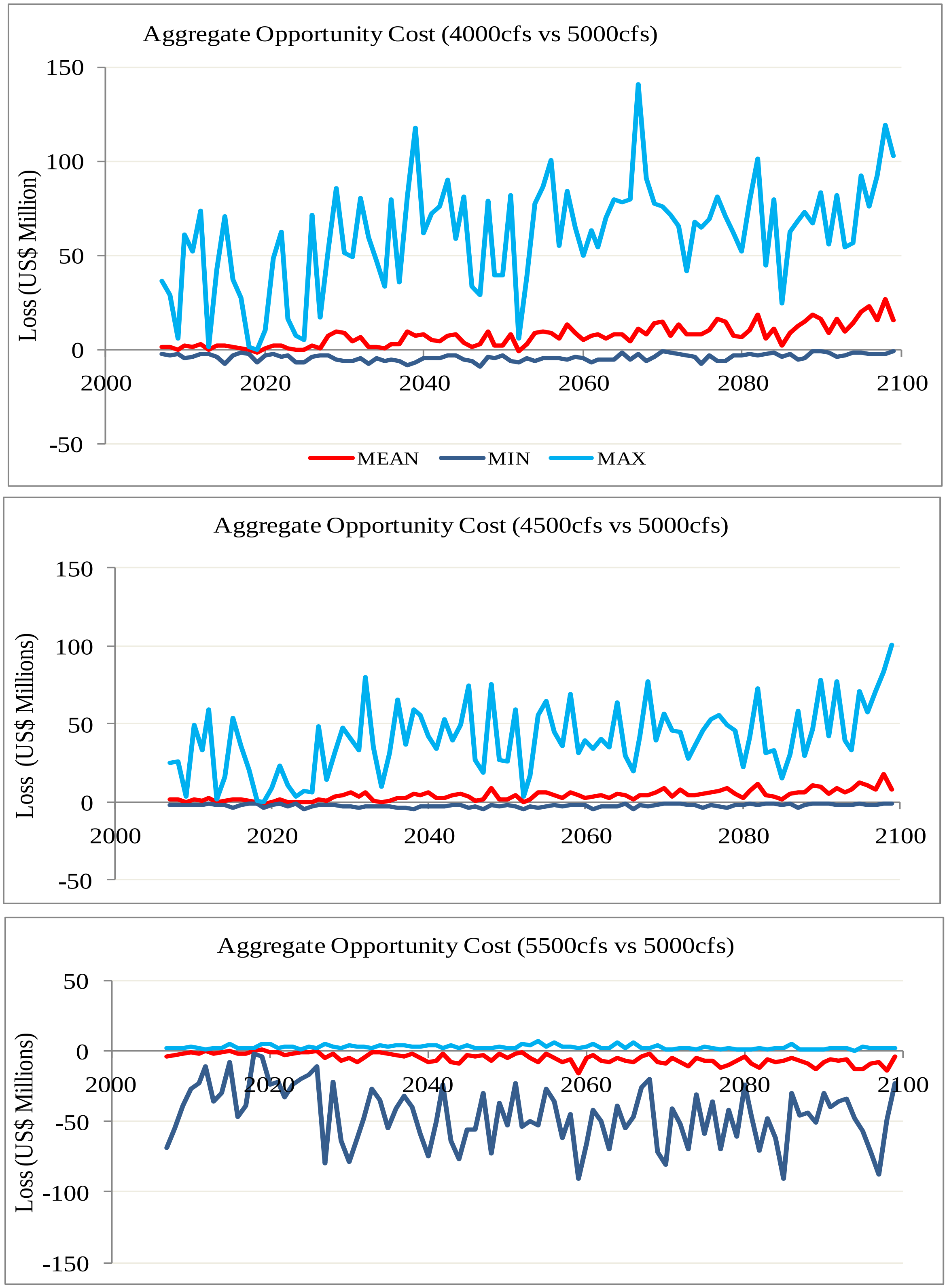


Figure 6.23: Aggregate Opportunity Costs under Different Chattahoochee Minimum Flow Requirements

6.2.3 Summary of Assessment Findings

Based on assessment of the physical and economic performance of the ACF system under different minimum environment flow requirements at the Chattahoochee gauge, it can be concluded that high minimum flow requirements impose high opportunity costs to upstream water users who have to forego water use to maintain the required minimum flows downstream. An increase in minimum flow constraint from 5000 cfs to 5500 cfs would result in foregone water use benefits of 0 to 91 million dollars annually depending on the climate change scenario. On the contrary, relaxing the constraint from 5000 cfs to 4500 cfs would result in savings of up to 101 million dollars. Relaxing the constraint further to 4000 cfs would result in savings of up to 135 million dollars annually. Besides the opportunity costs incurred, high minimum flow constraints also result in lower lake levels and high frequency of reservoir depletion and power generation failures.

6.3 Policy Scenario 3: Implementation of Water Supply Restrictions

This section focuses on assessment of the economic implications of water supply restrictions in the ACF basin. It is based on the assumption that the current basin water resources are fully committed to different competing uses and that there is no cheap alternative source of water to meet future demand. This implies that future demand growth can only be met through implementation of comprehensive demand management measures including efficient water use technologies, water recycling and re-use, and adoption of water conservation practices such as controlled out-door watering. Successful implementation of such measures requires significant investment in terms of infrastructure development, sensitization of the general public on good water use practices, research into efficient water use technologies, and strengthening of institutional coordination and stakeholder participation mechanisms. However, before such investment can be made, it is important to assess and understand the cost of taking no action. This helps in building a strong justification for use of public resources that would otherwise be used on other productive activities.

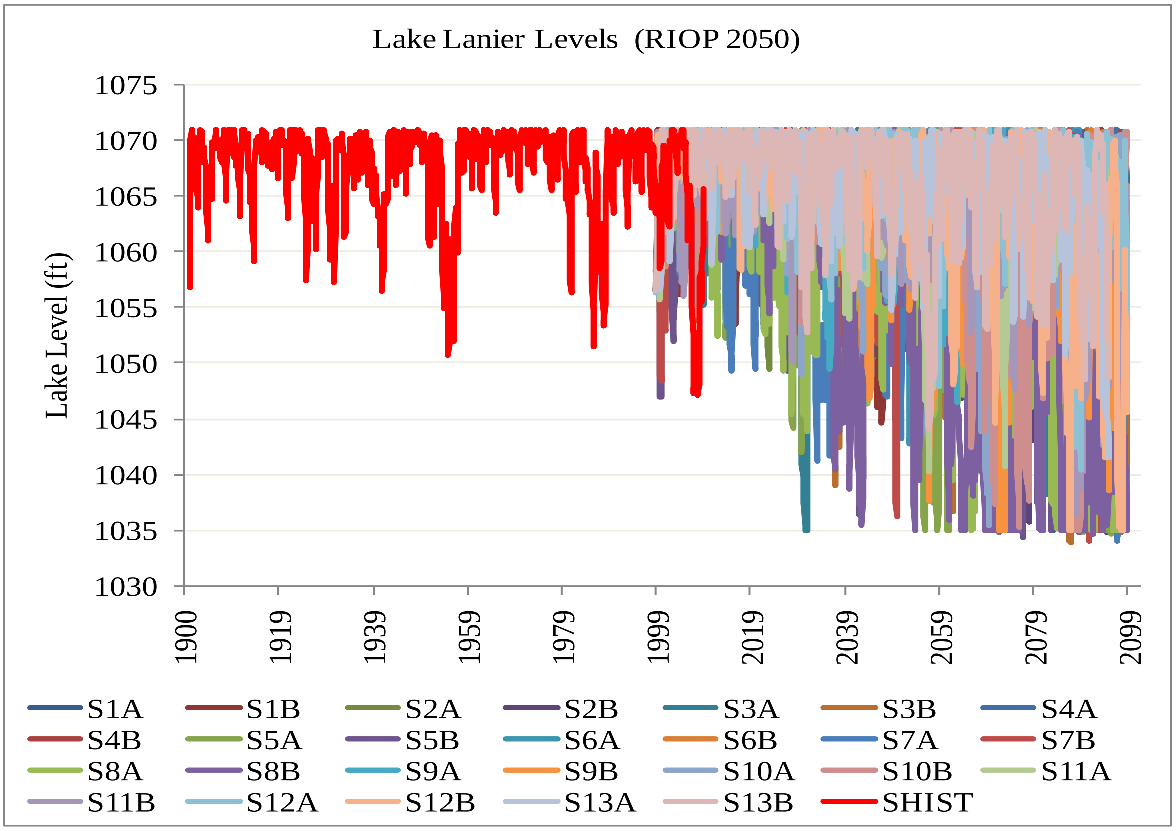
The objective is, therefore, to assess the economic implications of failing to meet future water demand growth in the basin by restricting water supplies to baseline (2007) levels. The assessment is two-fold: (i) Estimation of the impact of future demand growth and climate change on the system's physical outputs i.e. changes in reservoir levels, energy generation, water supply deficits, and in-stream flow fluctuations; (ii) Estimation of economic benefits/losses corresponding to the changes in physical outputs for each water use sector and for the entire basin. Two scenarios are considered corresponding to satisfaction of the baseline (2007) demand (RIOP 2007) and satisfaction of projected demand growth (RIOP 2050). Comparison of the two scenarios gives an indication of the economic implications of not putting in place necessary measures to cope with potential future water supply restrictions.

The Scenario assessment model of the ACF DSS is used to evaluate the performance of the ACF system under the two scenarios subject to future climate change, current minimum environmental flow constraints, and current reservoir operation policy (RIOP). At the end of each scenario run, the model generates sequences of all desired physical outputs including consumptive water demands at all nodes, weekly energy generation sequences at all generation facilities, reservoir levels and inflow and release sequences for all storage facilities in the system. These sequences are used to compare the changes in the physical outputs of the system under the two scenarios. They are also used as inputs into the economic assessment models that are used to estimate the corresponding changes in economic benefits.

6.3.1 Assessment of Changes in Physical Outputs

6.3.1.1 Fluctuation of Reservoir Water Levels

Figures 6.24 (a) and (b) show fluctuations in Lake Lanier levels and their corresponding frequency curves. Under the RIOP 2050, almost all the future frequency curves for the lake fall below the historical frequency curve implying that the lake is more likely to experience lower water levels under potential future climate conditions compared to the RIOP 2007 scenario. This is expected because meeting future water demand growth would require increased reservoir releases leading to lower reservoir levels and increased frequency of depletion. Figure 6.25 shows the frequency of reservoir depletion for the two scenarios. The figure depicts higher frequency of reservoir depletion under RIOP 2050 compared to RIOP 2007. Under the RIOP 2050, the frequency of depletion of Lake Lanier varies from 0 to 13 months over the entire assessment horizon, depending on the climate change scenario. The corresponding frequency is 0 to 5 months under the RIOP 2007 scenario. West Point does not experience any reservoir depletion whereas George and Woodruff follow the same pattern as Lake Lanier. Woodruff experiences depletion under only one climate change scenario compared to 12 under the two scenarios for both George and Lanier.



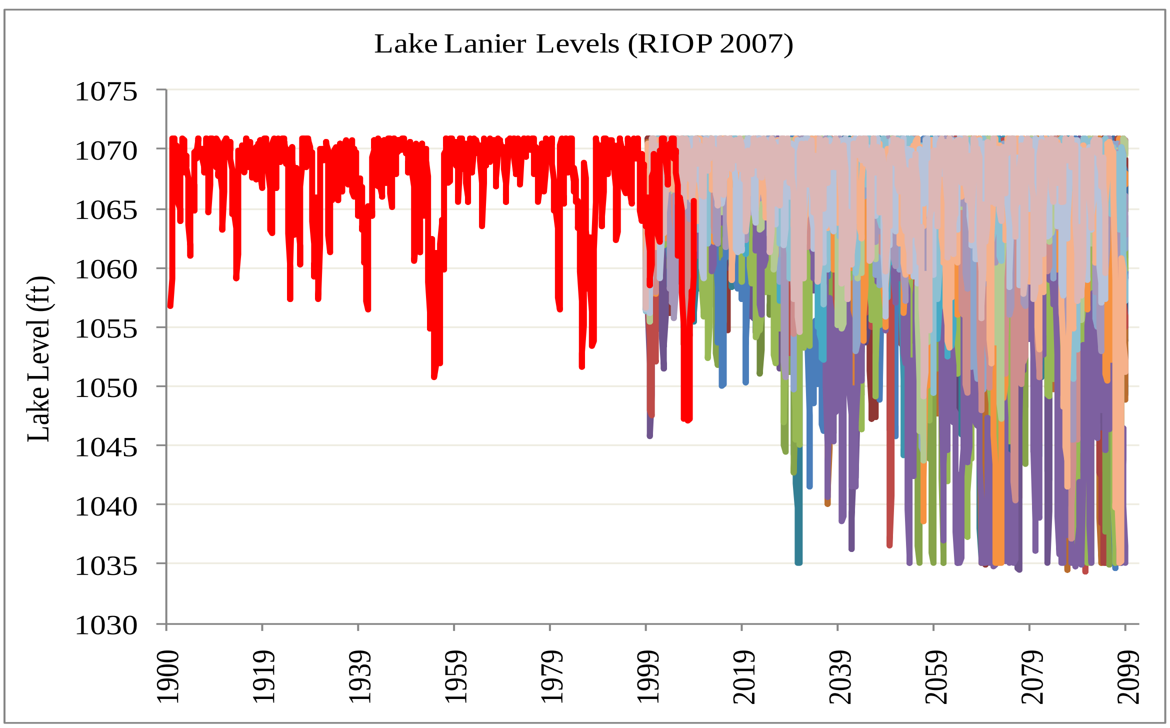
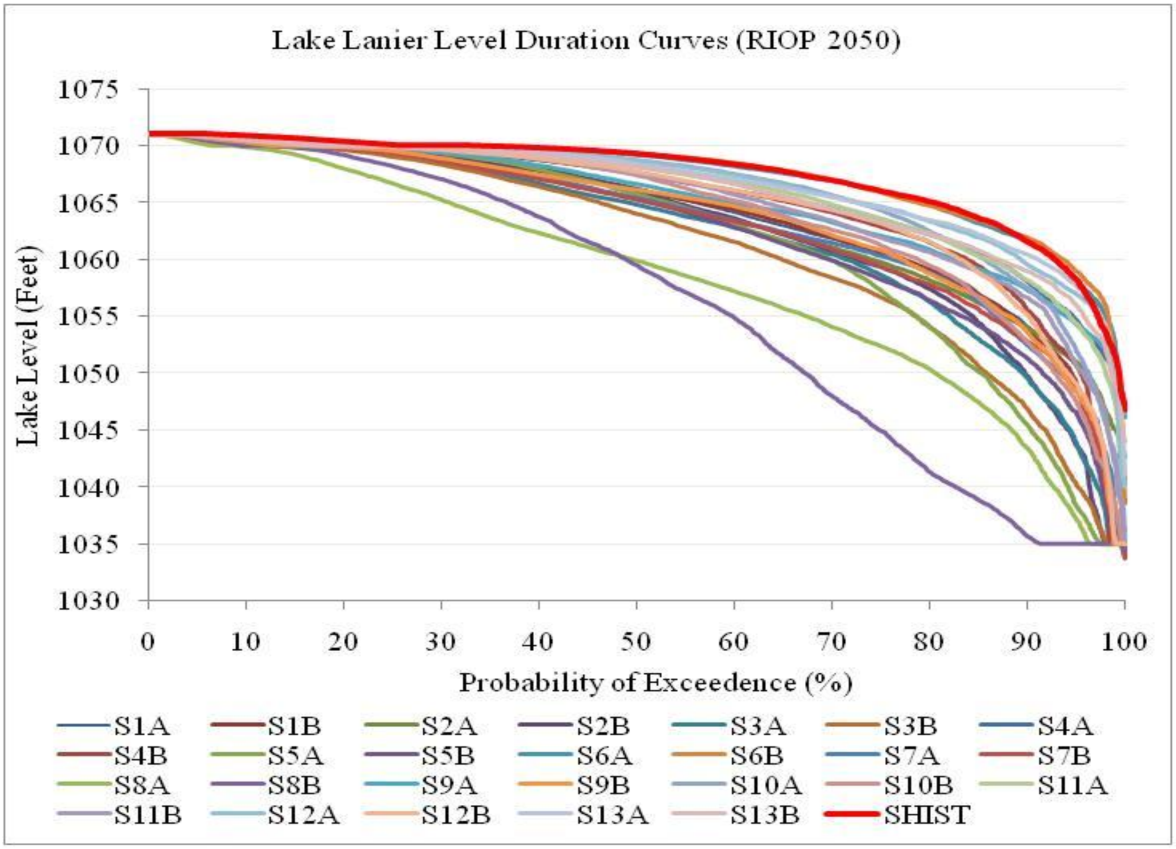


Figure 6.24 (a): Lake Lanier Level Fluctuation under Water Supply Restriction



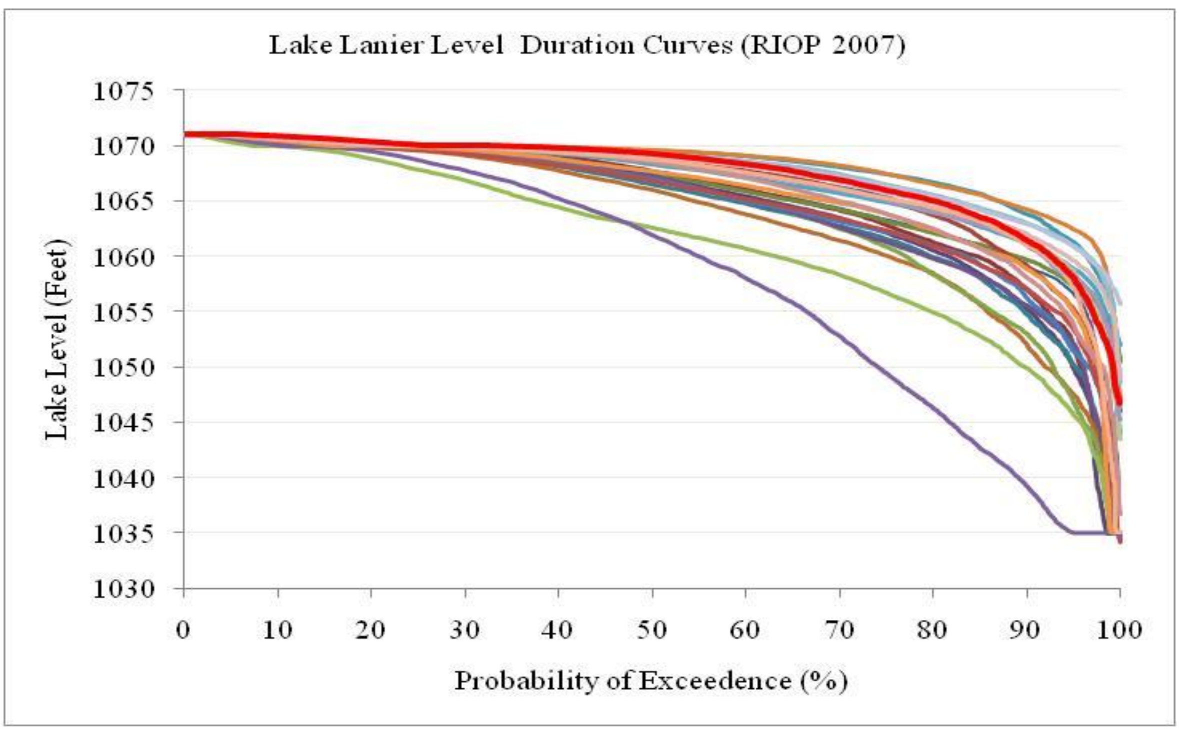


Figure 6.24 (b): Lanier Level Duration Curves under Water Supply Restriction

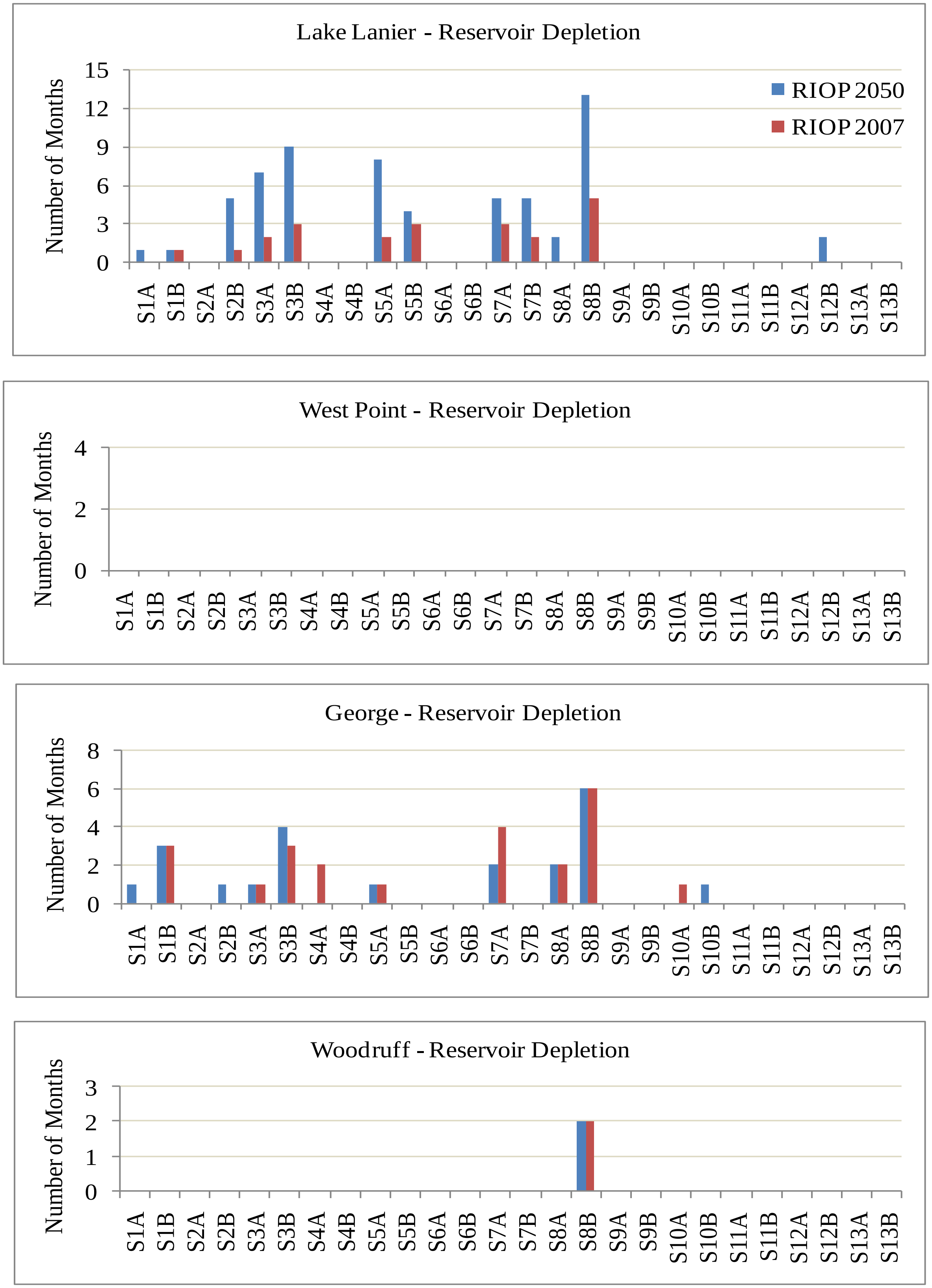
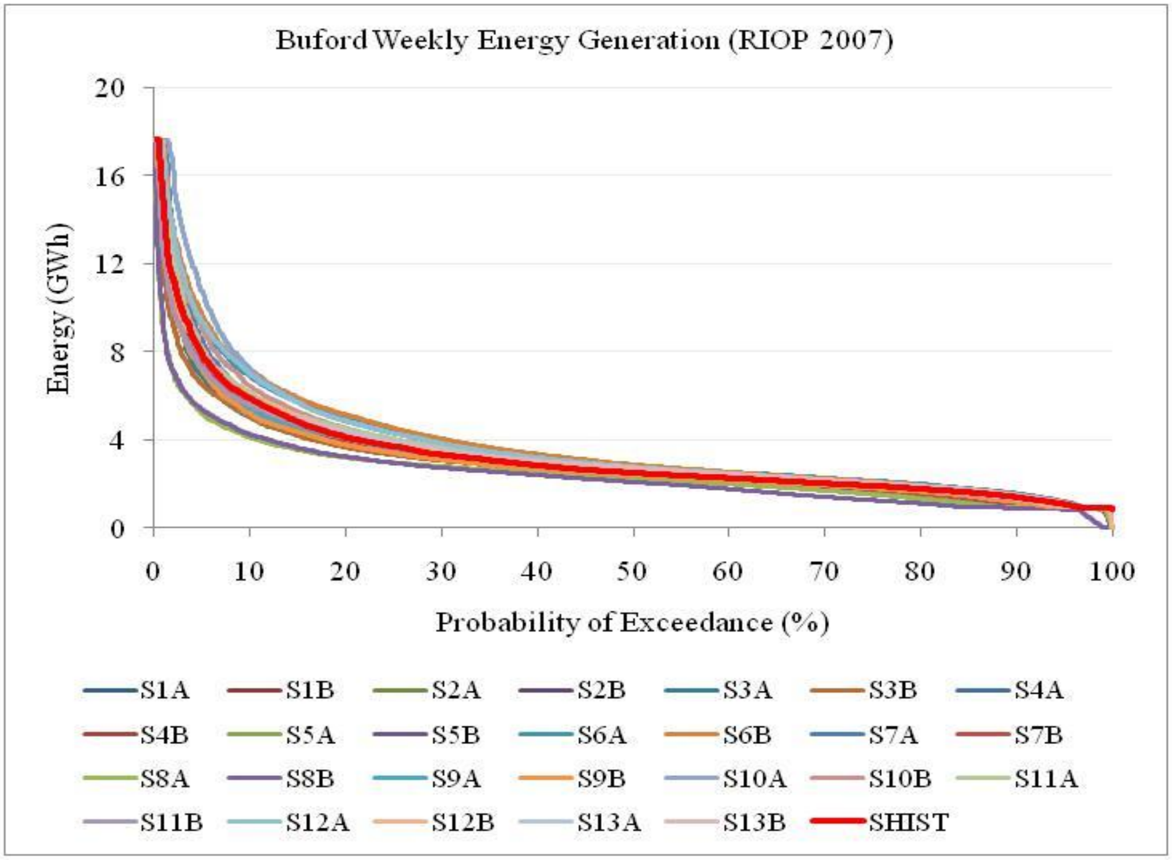
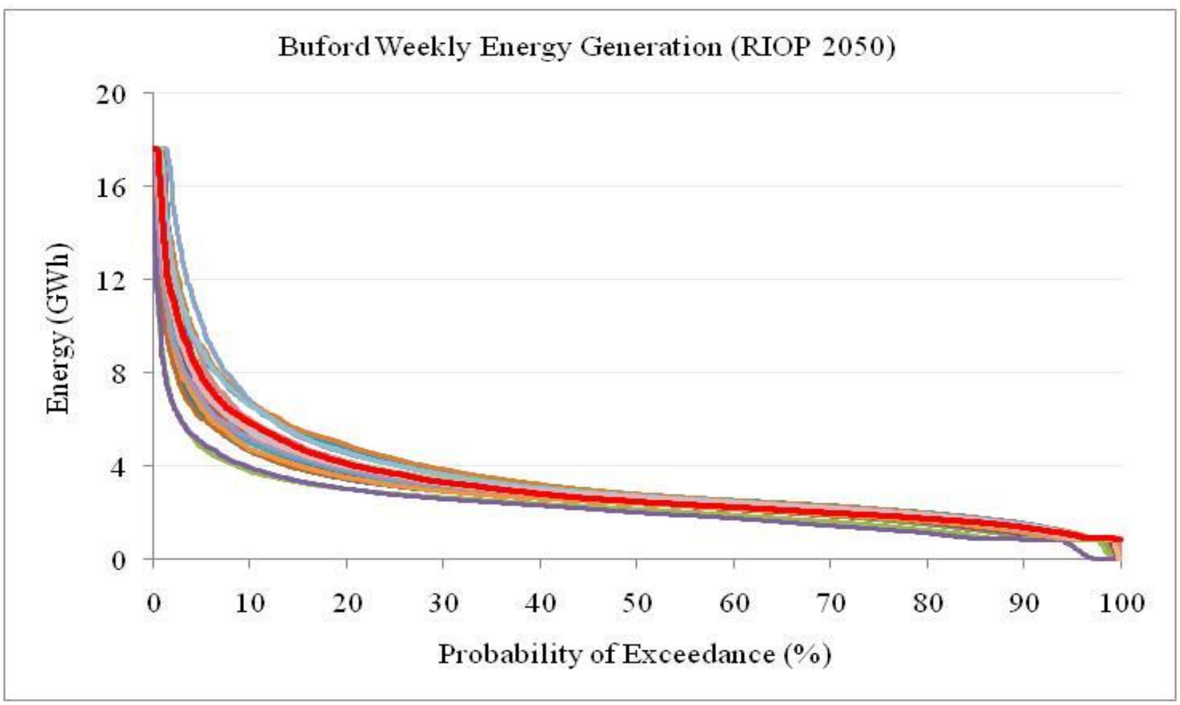


Figure 6.25: Potential Reservoir Depletion under Water Supply Restriction

6.3.1.2 Variability in Hydropower Generation

Figure 6.26 shows hydropower generation frequency curves for Buford. There is no significant difference in total average energy generation. Figure 6.27 shows the frequency of hydropower generation failure due to reservoir depletion. The figure depicts higher frequency of failure under RIOP 2050 compared to RIOP 2007. This is expected because RIOP 2050 is associated with higher frequency of reservoir depletion as discussed above. Under the RIOP 2050, the frequency of hydropower generation failure varies from 0 to 8 months over the entire assessment horizon, depending on the climate change scenario. The corresponding frequency is 0 to 3 months under the RIOP 2007 scenario. West Point does not experience any failure whereas George does in up to 3 months over the entire assessment horizon.





6.26: Buford Hydropower Generation Duration Curves under Water Supply Restriction

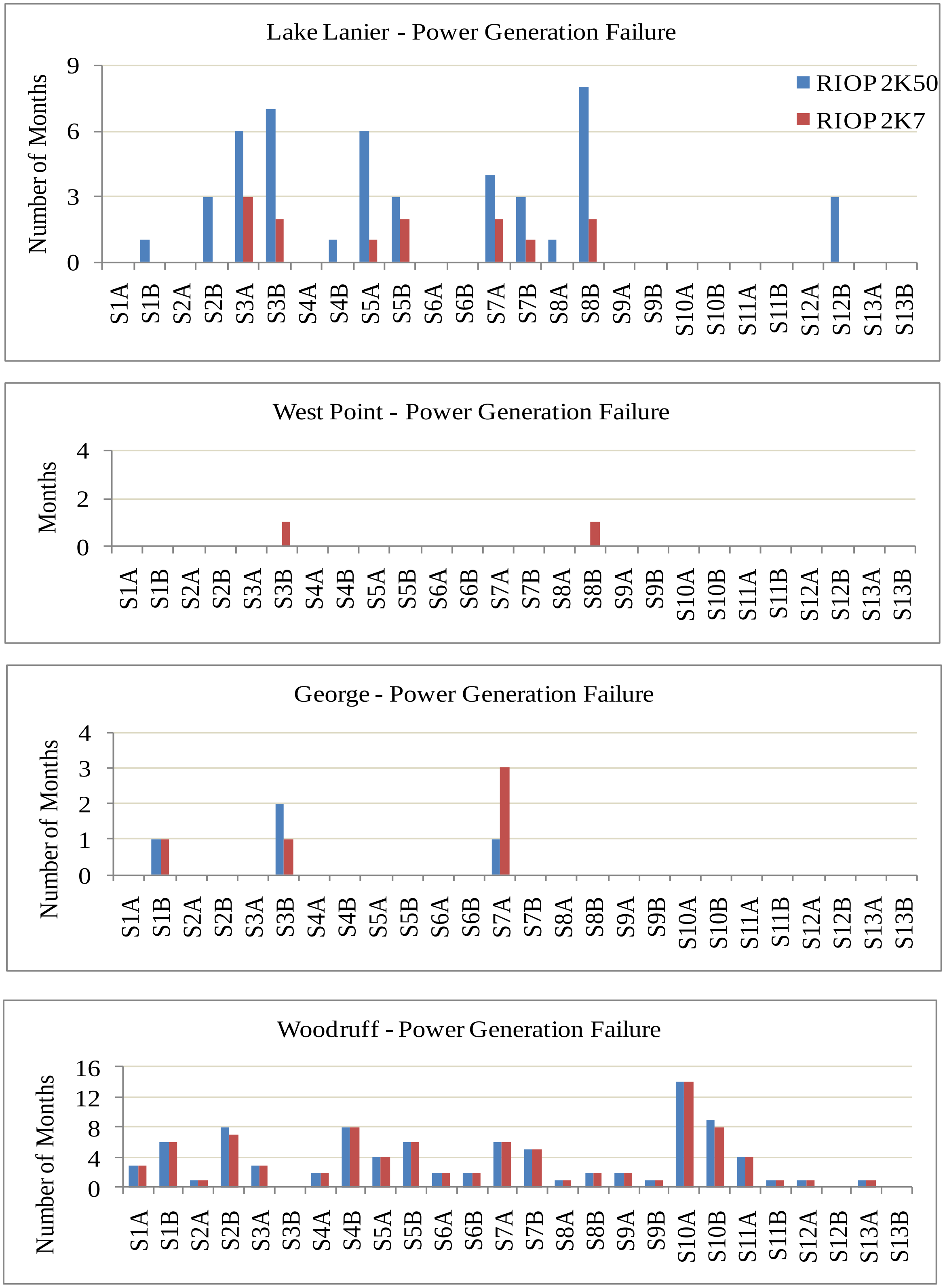


Figure 6.27: Hydropower Generation Failure Water Supply Restriction

6.3.1.3 Violation of Minimum In-stream Flow Requirements

Figure 6.28 shows the frequency of violation of the minimum environment flow constraint at the Chattahoochee gauge. The figure depicts more violations under RIOP 2050 compared to RIOP 2007. This is expected because RIOP 2050 is associated with higher consumptive water withdrawals compared to RIOP 2007. The violations range from 0 to 163 months under the RIOP 2050 and 0 to 158 months under the RIOP 2007 scenario over the entire assessment horizon, depending on the climate change scenario. The violations occur in 25 out of the 26 climate scenarios under the RIOP 2050 and in 23 of the climate scenarios under RIOP 2007. Figure 6.29 shows frequency curves for Chattahoochee gauge monthly flows over the assessment horizon.

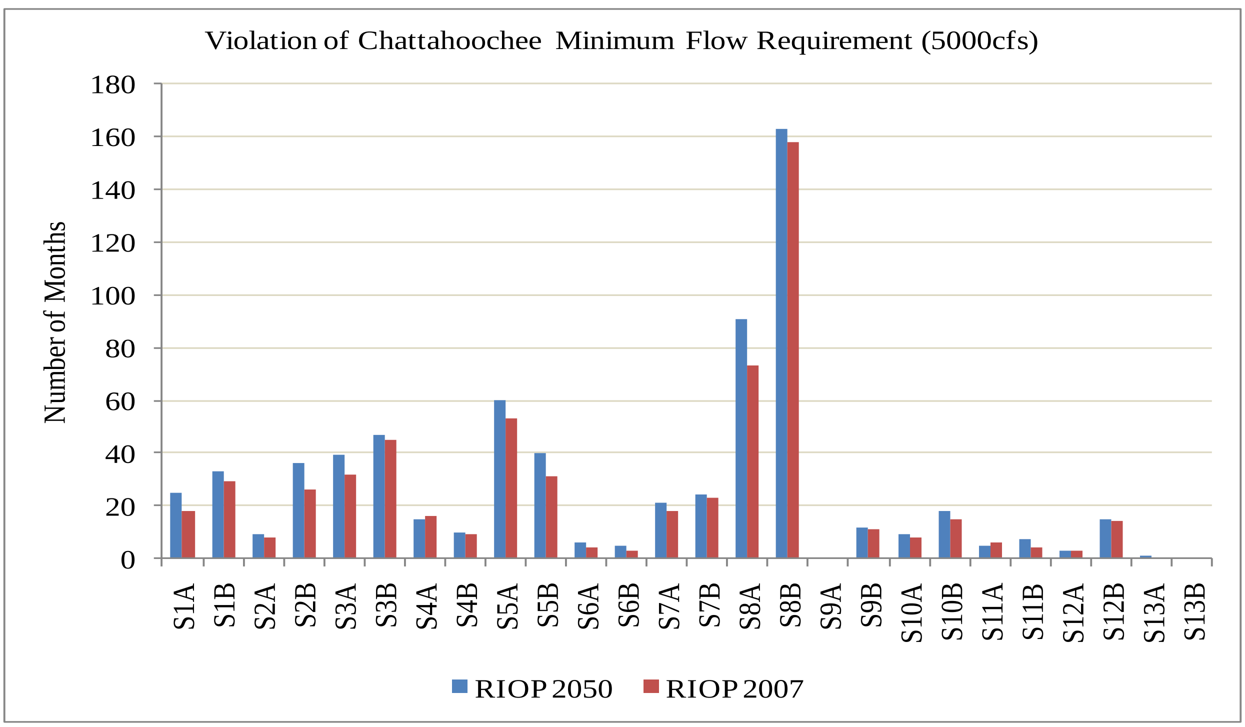
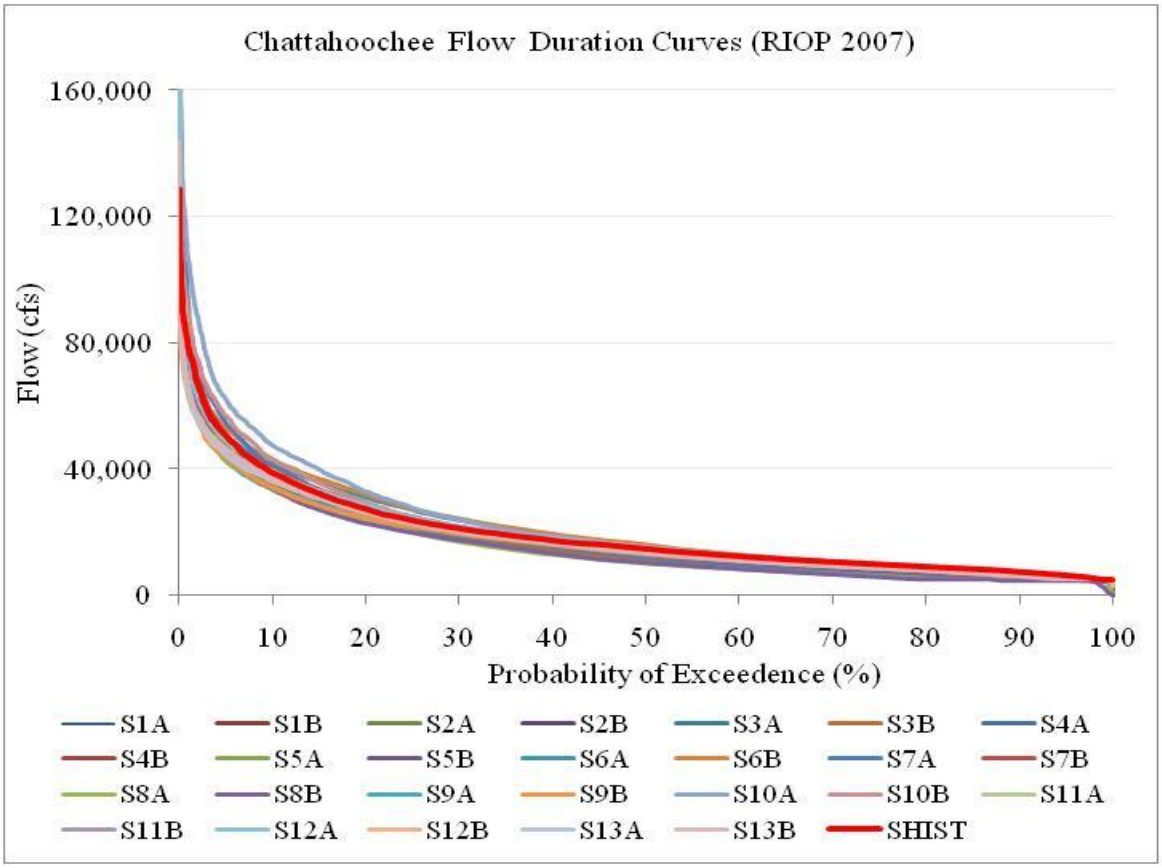


Figure 6.28: Violation of Chattahoochee Minimum Flow Requirement under Water Supply Restriction



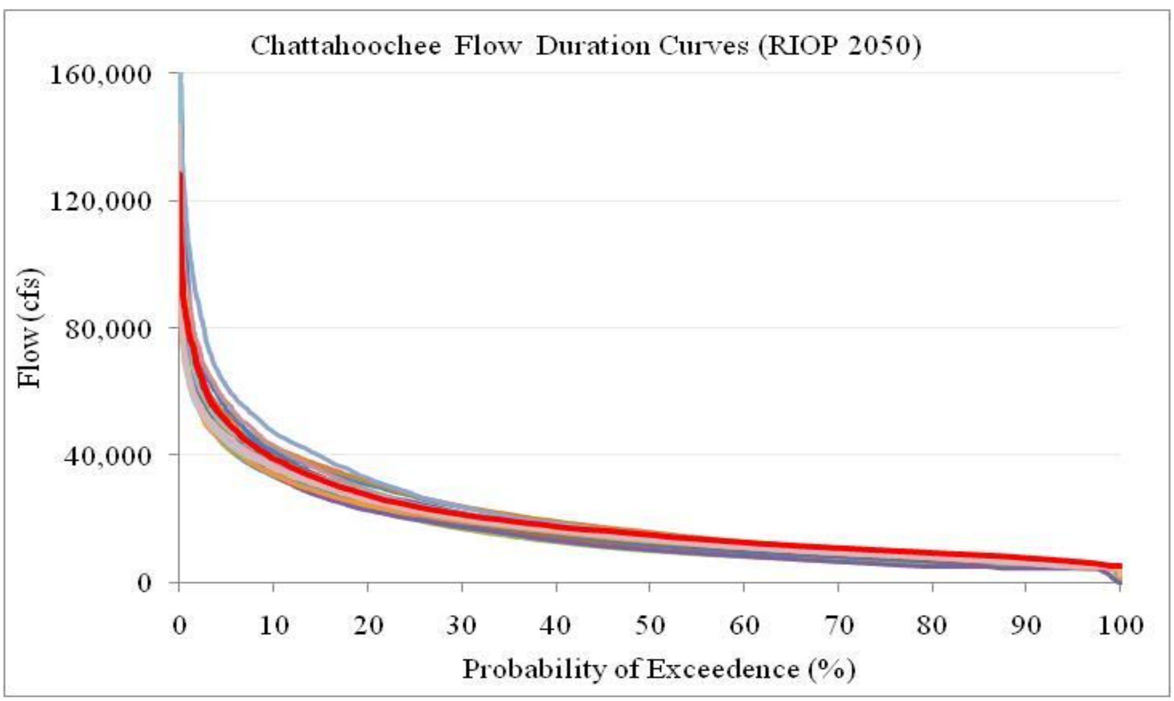


Figure 6.29: Chattahoochee Flow Duration Curves under Water Supply Restriction

6.3.1.4 Water Supply Deficit

Figure 6.30 shows the total water supply deficits under the two scenarios. The water supply deficit is higher under the RIOP 2050 scenario compared to the RIOP 2007 scenario due to higher consumptive water withdrawals. The total deficits range from 0 to 3102cfs under the RIOP 2050 and 0 to 666cfs under the RIOP 2007 scenario, depending on the climate change scenario. The deficits happen in 25 out of the 26 climate change scenarios and are highest under the drier scenarios. Figure 6.31 shows annual water deficits under the two scenarios. Annual deficits range from 0 to 360cfs with most of them occurring towards the end of the horizon when demand is greatest.

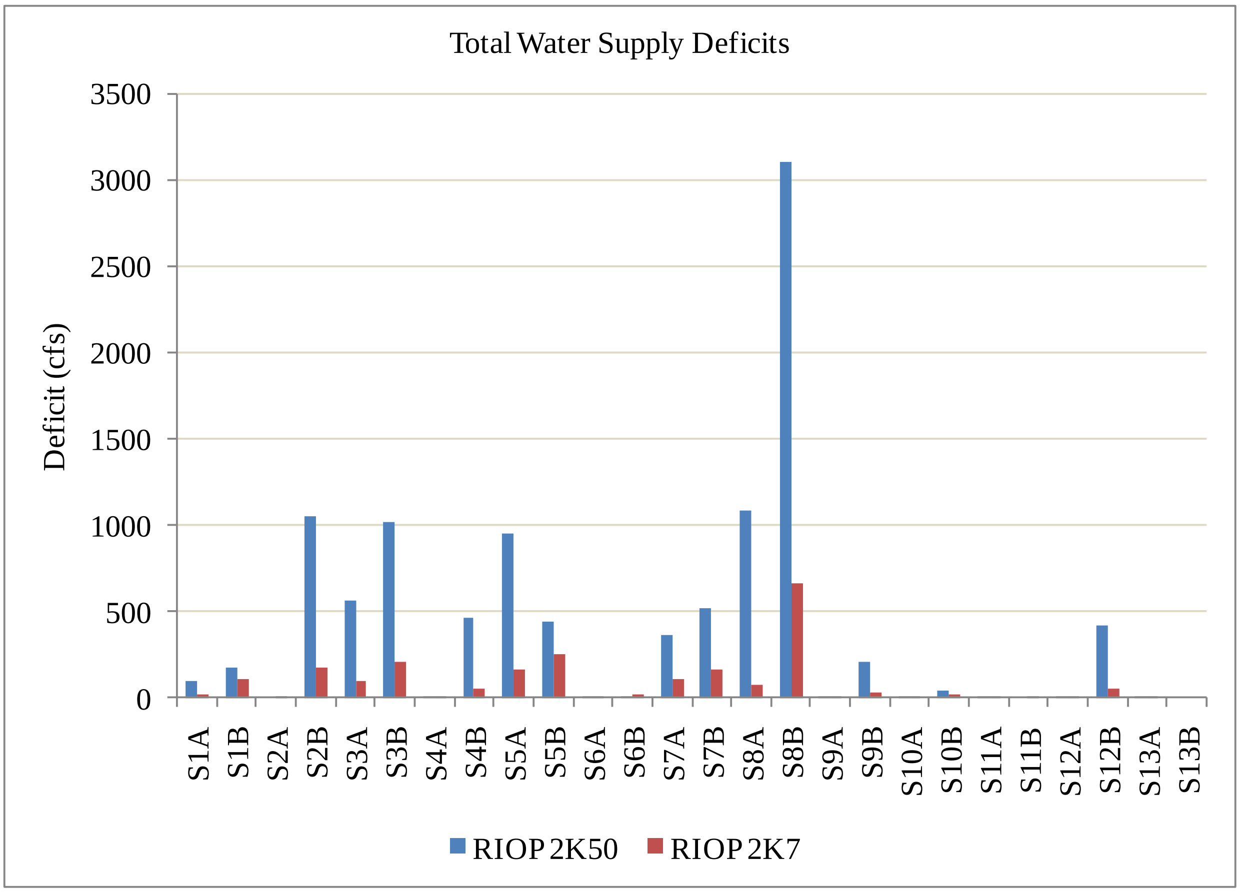
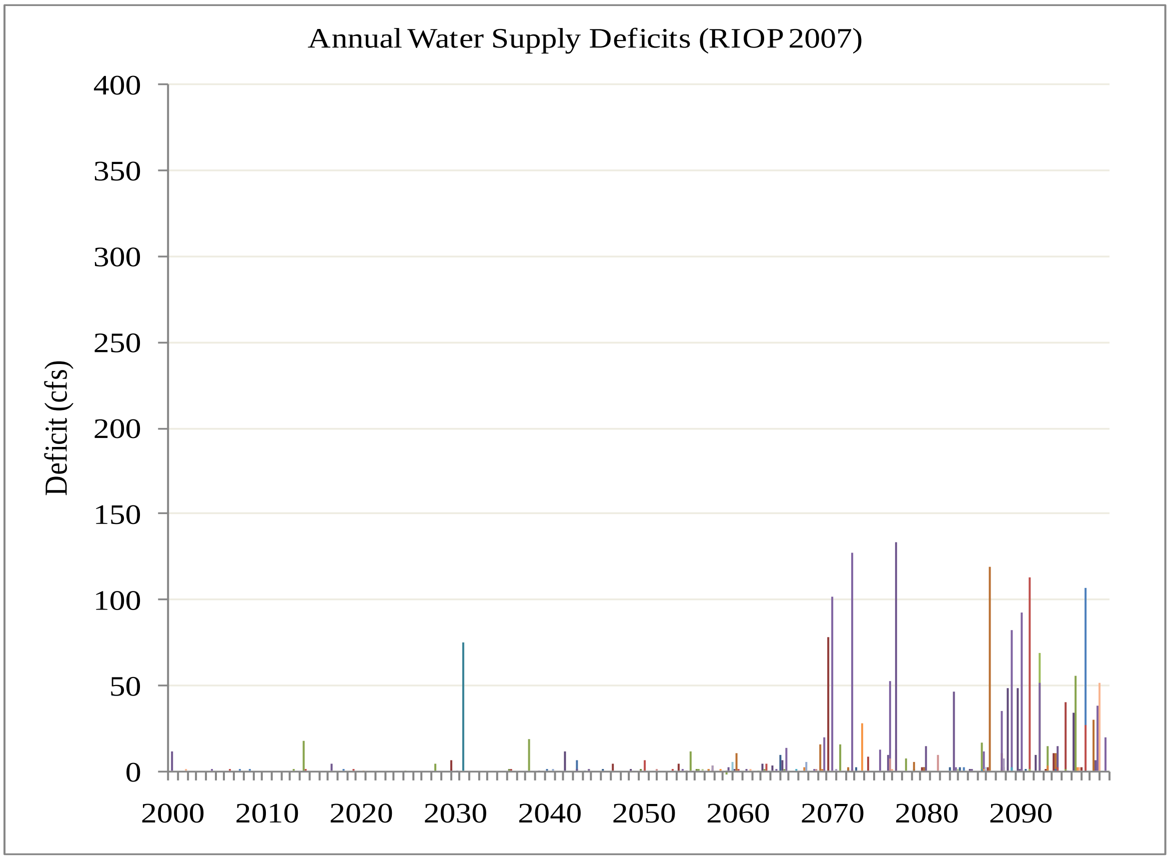


Figure 6.30: Total Water Supply Deficit under Water Supply Restriction



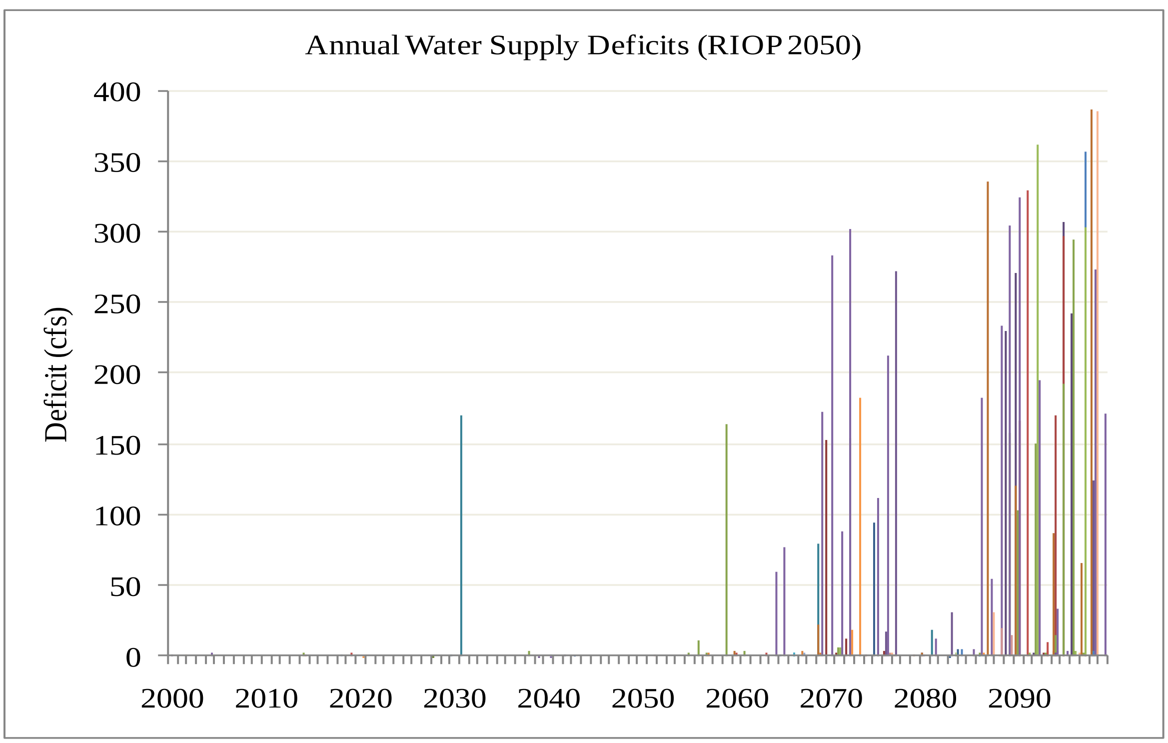


Figure 6.31: Annual Water Supply Deficit under Water Supply Restriction

6.3.2 Assessment of Economic Benefits

6.3.2.1 Recreation Water Use Benefits

Figure 6.32 shows bounds for the difference in annual recreation benefits between the two scenarios under all climate change scenarios. Recreation benefits under RIOP 2007 are consistently higher than those under RIOP 2050 due to the tendency for lake levels to stay higher under RIOP 2007 compared to RIOP 2050. The difference increases with time over the assessment period due to the systematic increase in water withdrawals to meet the growing demand under RIOP 2050. The difference in annual recreation benefits ranges from 0 to 134 million dollars depending on the climate change scenario.

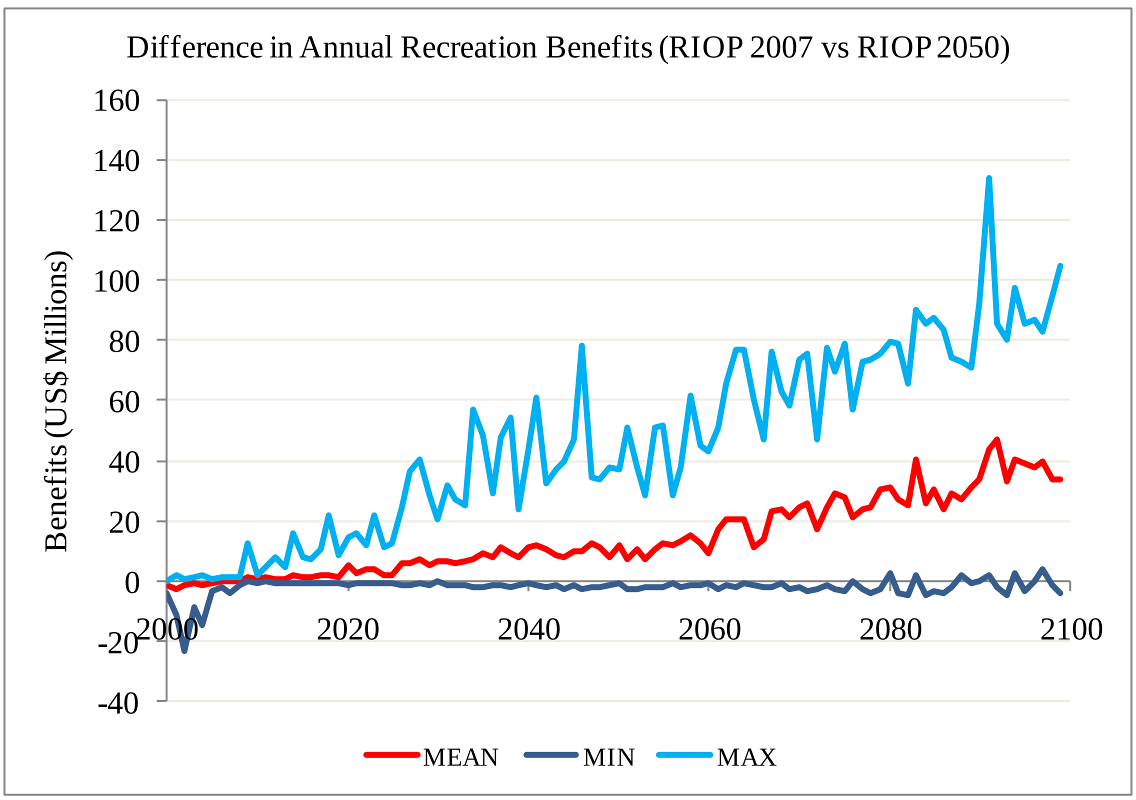


Figure 6.32: Difference in Annual Recreation Benefits under Water Supply Restriction

6.3.2.2 Municipal Water Use Benefits

Figure 6.33 shows the difference in annual municipal water supply economic loss (measured in terms of loss of consumer surplus). The difference grows steadily from 0 to about 1.5 billion dollars due to the systematic growth in municipal water demand over the assessment period. The difference depicts the loss in consumer surplus associated with growing water supply deficits under RIOP2007 due to water supply restrictions. On the contrary, since there is no water supply restriction under RIOP 2050, the loss in consumer surplus is much smaller.

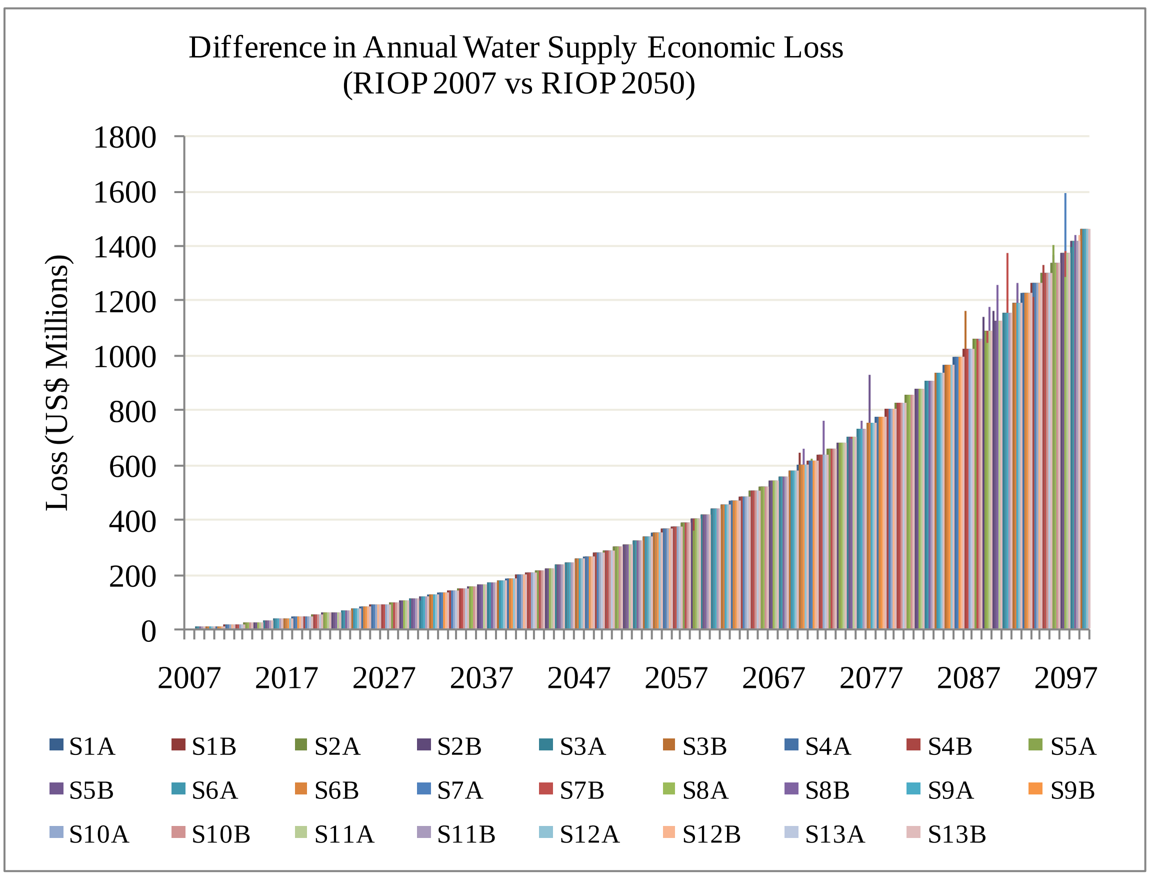


Figure 6.33: Difference in Annual Municipal Water Supply Economic Loss under Water Supply Restriction

6.3.2.3 Irrigation Water Use Benefits

Figure 6.34 shows the difference in annual irrigation loss due to water supply restrictions. The loss increases steadily from 0 to about 0.5 million dollars under the driest climate scenario. The steady increase in the difference is due to the systematic increase in irrigation water demand that is not met due to water supply restrictions under RIOP2007.

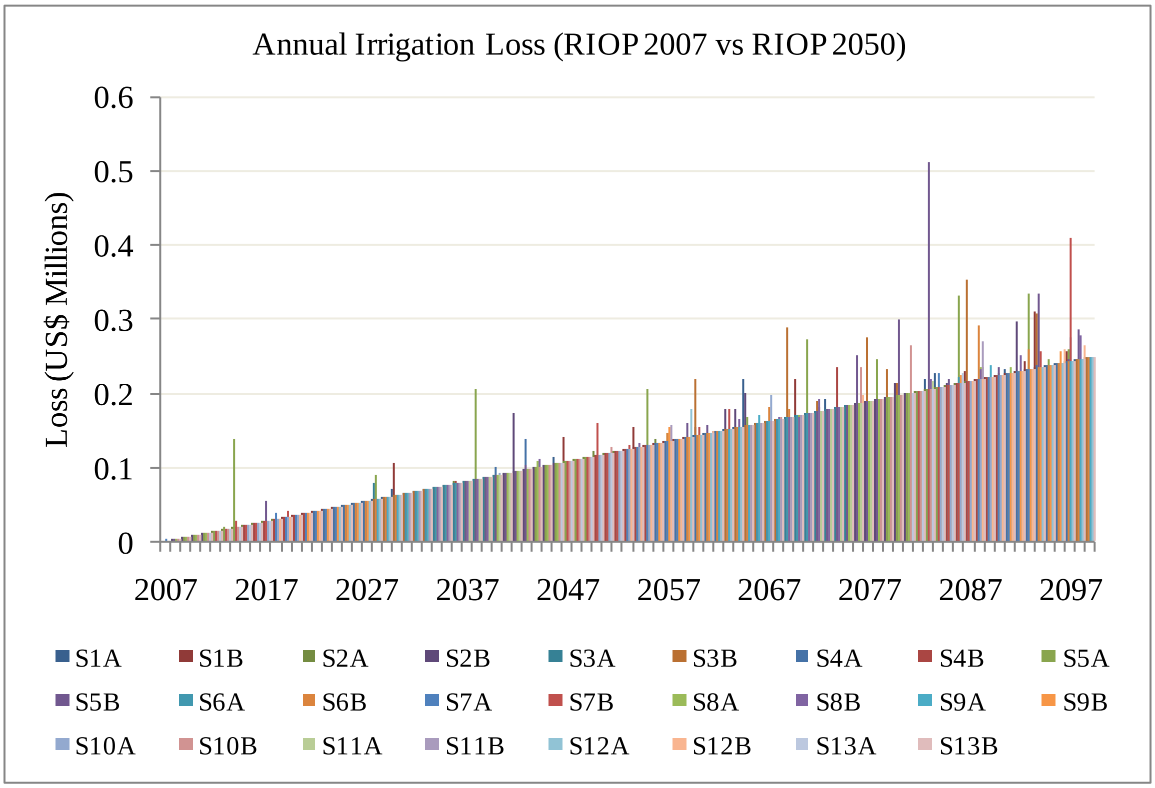


Figure 6.34: Annual Irrigation Loss under Water Supply Restriction

6.3.2.4 Hydropower Generation Benefits

Figure 6.35 shows bounds for the difference in annual hydropower benefits between the two scenarios under all climate change conditions. The difference in annual benefits ranges between -4.7 to 15.6 million dollars depending on the climate change scenario. The difference is small in the beginning and increases over the assessment horizon due to steady increase in water withdrawals under RIOP 2050 which tends to keep lake levels lower and negatively impact hydropower generation.

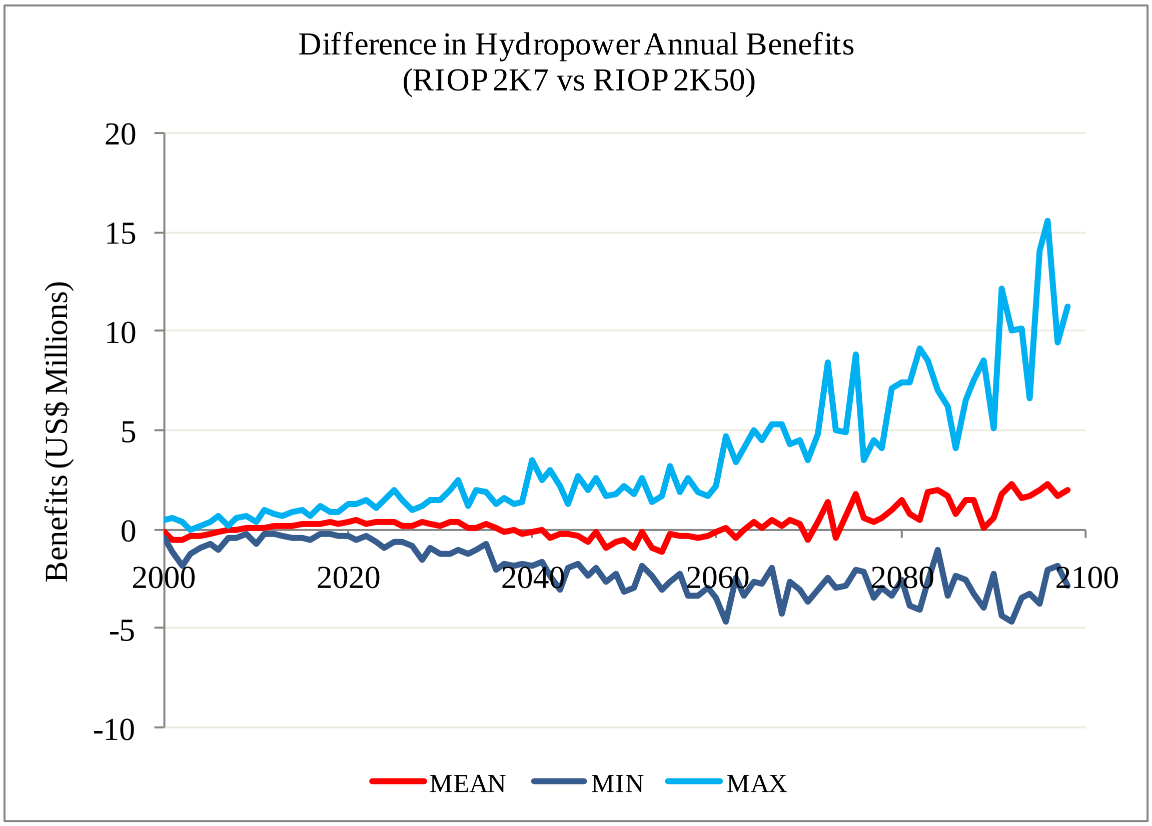


Figure 6.35: Difference in Hydropower Annual Benefits under Water Supply Restriction

6.3.2.5 <u>Thermal Power Water Use Benefits</u>

No Thermal Power losses are incurred because thermal water cooling requirements are satisfied all the time under RIOP 2007 and RIOP 2050.

6.3.2.6 Aggregate Water Use Benefits

Figure 6.36 shows aggregate annual economic loss due to water reallocation from consumptive to non-consumptive uses. The annual loss ranges from 0 to 1.3 billion dollars. The loss is significant and shows the price consumers would be willing to pay to avert potential water supply deficits in future. Such economic information is useful to help water decision makers plan ahead and make the necessary investments to avert future water supply shortages.

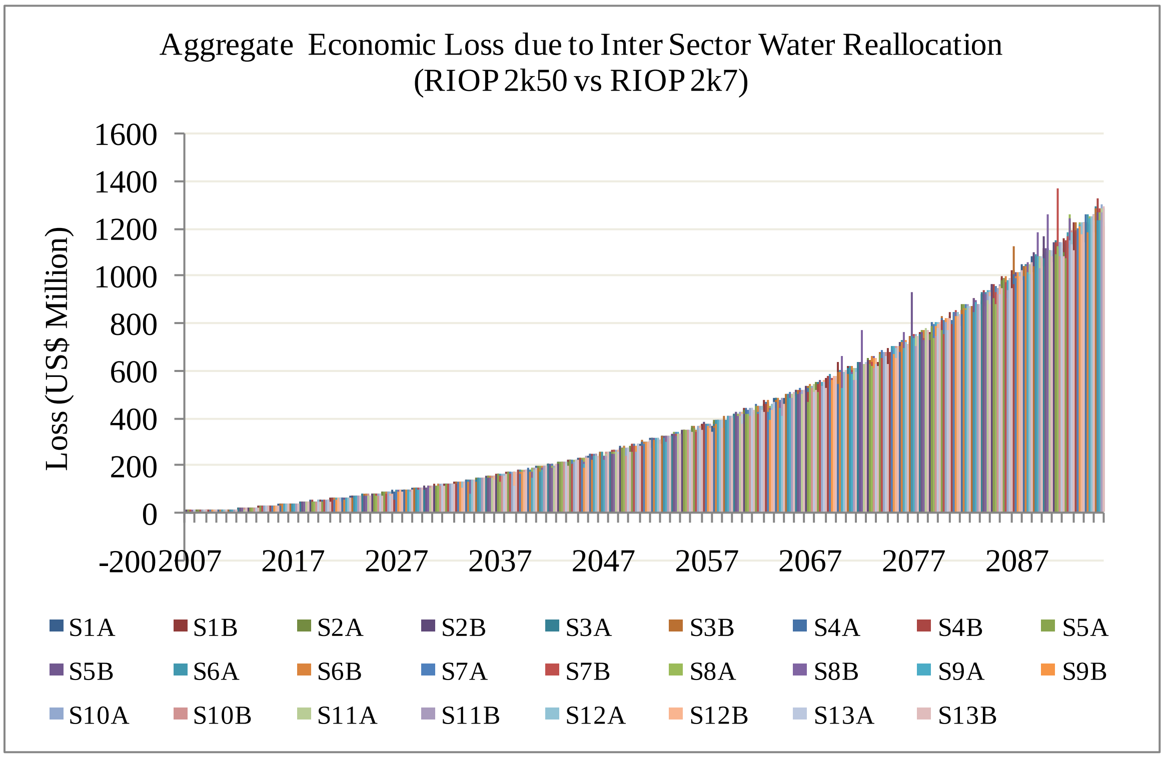


Figure 6.36: Aggregate Annual Economic Loss under Water Supply Restriction

6.3.3 Summary of Assessment Findings

Based on assessment of the physical and economic performance of the ACF system under RIOP 2K7 and RIOP 2K50, it can be concluded that water supply restrictions impose heavy costs to water users in the basin and appropriate measures should be put in place to minimize their impacts. Restricting water supplies to current levels over a long period of time (up to 2099) results in significant losses (up to US$ 1.3 billion) to water users. The loss, which occurs mostly in the municipal water supply sector, far outweighs the non-consumptive water use benefits. It is therefore important that before any water supply restrictions are implemented in the basin, a thorough economic analysis is undertaken to assess and understand their potential economic implications on each water use sector to guide the water rationing process.

CHAPTER 7: CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

This research set out to develop and apply a detailed hydro-economic modeling tool to support multi-objective water resources assessments. The motivation for this work is the inherent weaknesses in commonly used hydro-economic tools that usually seek to only maximize expected net benefits. This risk neutral expression, however, ignores the desire of most decision makers to avoid severe consequences of extreme (albeit unlikely) events. For example a manager of a hydropower generation facility is not only interested in knowing how much the profit will be in the future but, equally importantly, on understanding the frequency and duration of potential reservoir depletion and corresponding power generation outages. The frequency and severity of these extreme events could have serious legal and contractual implications that outweigh the expected profits. Having full understanding of the economic and physical performance of the facility can enable managers to evaluate the level of risk involved and put in place appropriate mitigation measures to minimize impacts of extreme events and thus safeguard his operations.

The research objective has been achieved through development of a tool that provides for integrated assessment of physical and economic impacts of diverse management and policy changes on a basin’s water resources under historical and future climatic conditions. A modular modeling approach was adopted in which detailed economic and water resources assessment modules were developed separately and linked through backward and forward exchange of output data between the different modules.

The tool was applied to the Apalachicola- Chattahoochee-Flint (ACF) Basin as a case study. However, the methodologies are generic and are applicable to any other basin in the world. The ACF basin is particularly important as a source of drinking water supply to the Atlanta Metropolitan Area, one of the fastest growing metropolitan areas in the US. ACF basin water resources also support one of the most vibrant agricultural sectors in the US estimated to generate more than 50 billion dollars annually in direct and indirect economic benefits.

The assessments conducted were two-fold:

(1) Baseline Hydro-economic Assessments – to simulate the physical and economic performance of the ACF system under baseline conditions of current water resources management objectives, minimum environmental flow constraints, existing reservoir operation policy, and other system constraints.

(2) Water Resources Policy Assessments – to simulate the physical and economic performance of the ACF system under three potential water management scenarios, i.e., (a) implementation of an alternative reservoir operation policy; (b) relaxation of existing minimum environmental flow constraints; and (c) water supply restrictions.

7.1.1 Summary of Key Findings

(1) The baseline assessment highlights significant changes in physical and economic performance of the ACF over the next 100 years due to increasing pressure on the basin's water resources. The basin is expected to experience reduction in water supply and increase in water demand due to climate and demographic changes. The basin is likely to experience significant reduction in runoff from its watersheds due to projected increase in evapotranspiration associated with higher temperatures in future. Water demand

projections indicate significant increase in demand especially in the municipal water supply sector. However, implementation of planned investments in efficient water use technologies and improved drainage infrastructure would result in increased return flows there by minimizing aggregate consumptive water use in the basin. Decreased watershed runoff will have a negative impact on reservoir levels and associated non-consumptive water uses that rely on them (e.g. hydropower generation, recreation, and ecological uses). Municipal water demand is estimated to increase from the current 965 cfs to 1545 cfs, an increase of about 60%. Increase in irrigation water demand is expected to be milder (less than 10%).

(2) Decreased watershed runoff and increased water demand will result in a steady growth in water supply deficits and decline in lake levels. Annual water supply deficits are projected to increase from their current level (less than 20 cfs) to as high as 130 cfs during extreme droughts in the later part of the century. Moreover the frequency of deficits will also intensify with time. Decline in lake levels will have a negative impact on all non-consumptive water uses whose output will steadily decline over time. It is therefore important that water managers and decision makers in the basin begin the process of formulation and systematic implementation of appropriate intervention measures to minimize the impacts of these challenges.

(3) Water resources policy assessment results demonstrate the existence and benefits of potential intervention measures that could be implemented to minimize impacts of anticipated water demand growth and potential climate change. The assessments highlight: (a) significant economic loss incurred by water users due to water scarcity and inefficient water use; (b) the benefits of adaptive water resources management through

implementation of more efficient reservoir operation and management policies; and (c) economic implications of water supply restrictions.

Intervention measures range from review of existing water resources management policies in the basin to investment in water infrastructure, research, and efficient water use technologies. Assessment of the physical and economic impacts of some of these measures yielded the following results:

(a) It is possible to improve efficiency of operation of reservoirs in the basin by modifying the existing operation policy. Implementation of an alternative policy (GTOP) results in incremental aggregate annual benefits 83% of the time to the magnitude of 93 million dollars annually. Besides the economic benefits, GTOP also performs better than RIOP in terms of physical outputs, i.e., it results in higher lake levels, less frequency of reservoir depletion and power generation failures, and less violations of minimum flow requirements at critical river sections. GTOP's strength as an adaptive reservoir management policy makes it a technically viable mitigation measure against potential negative impacts of future climate change on the basin's water resources.

(b) High minimum environmental flow requirements impose high opportunity costs on upstream water users who have to forego water use to maintain the required minimum flows downstream. An increase in minimum flow constraint from 5000 cfs to 5500 cfs would result in foregone water use benefits of up to 90 million dollars annually while relaxing the constraint from 5000 cfs to 4000 cfs would result in savings of up to 140 million dollars annually. Besides the opportunity costs incurred, high minimum flow constraints also result in lower lake levels and high frequency of reservoir depletion and power generation failures.

Though it is generally acknowledged that the value of environmental services provided by the basin's aquatic ecosystems is significant and could potentially outweigh the opportunity costs borne by upstream water users, little research has been undertaken to try and estimate the monetary value of these benefits. This undermines the legitimacy of the process of setting minimum environment flow requirements in the basin since it looks quite arbitrary to upstream water users. Comprehensive assessment of the economic benefits of environment water use would provide a sound and transparent economic justification for the specified minimum environment flow requirements and would inform stakeholder discussions regarding efficient water allocation in the basin.

(c) Water supply restrictions have the potential of imposing significant economic losses on the basin riparians. For example, restriction of off-stream water withdrawals to baseline (2007) levels could result in aggregate annual economic losses of up to 1.3 billion dollars under future climate change conditions. The loss, which occurs mostly in the municipal water supply sector, far outweighs the non-consumptive water use benefits. It is therefore important that before any inter-sector water reallocations are considered in the basin in future, thorough economic analysis should be undertaken to assess and understand their potential economic implications on each water use sector.

In conclusion, this research provides a holistic analytical framework that can be used to generate significant information useful for multi-objective water resources decision making in a river basin. This information is useful in generating consensus on potential win-win management and development options for a given water basin.

7.2 Recommendations for Future Work

The outcomes of this research set a foundation for potential future work in this subject area. The following specific recommendations are made regarding future research areas to expand this work:

(1) Consideration of additional water use sectors – This research focused on only five water sectors in the basin, i.e., irrigation, municipal water supply, hydropower generation, recreation, and thermal power cooling water requirements, and other sectors through sensitivity analysis and shadow price considerations. Though this list includes most of the major water use sectors, it does not explicitly address other important water uses like environment water use, aesthetic impact of water bodies on the housing sector, navigation, and fisheries sector. Consideration of these other water uses would improve on the economic value estimates computed in this work.

(2) Evaluation of a wider range of water resources management policies – As stated earlier, the strength of hydro-economic tools lies in their ability to support comprehensive physical and economic assessments of diverse water resources management policy changes. Several potential policy options aimed at improving water resources management and use efficiency can be identified and evaluated for the ACF basin. This research considered only a few of them. Future work should broaden the scope of policy options to include, among others, water infrastructure development, introduction of water trading markets, adoption of water use efficiency technologies, implementation of water conservation and recycling measures, and identification of new water sources (e.g., inter basin transfers and desalination). Future work could also include assessment of the performance of the system subject to implementation of multiple policy changes.

(3) Comparison of a modular versus a holistic modeling approach – A modular modeling approach was used in this research where detailed economic and water resources assessment modules were developed separately and linked through backward and forward exchange of output data. The main strength of the modular approach is its ability to go into more detail in each sub-field, and the ability to be independently updated and developed. On the other hand, holistic models can more effectively represent causal relationships and interdependencies between the physical and economic processes in the basin. In addition, scenario-based studies such as climate change impact studies are easier to execute with holistic models since they do not require representing the changed policies or conditions separately for each sub-model. Though the modular approach was the preferred approach in this research, the holistic approach has advantages which could be leveraged and comparisons made to determine what the added value is in adopting one approach over the other.

APPENDIX A: ACF RESERVOIR OPERATION POLICY

Authority for management of the four federal reservoirs in the ACF basin is vested with the US Army Corps of Engineers who are mandated, through an Act of Congress, to coordinate operation of the facilities, on behalf of the Federal Government, to ensure achievement of their intended objectives. The original operation policy of the federal reservoirs was congressionally authorized and is outlined in the 1989 Draft Master Water Control Manual. According to the policy, the Corps of Engineers is required to utilize action zones to determine minimum hydropower generation, water supply and water quality releases at each project as well as maximum navigation releases from conservation storage while balancing the levels in all reservoirs. During low flow periods, the policy requires that water be taken first from storage in the lower reservoirs in the system and gradually pulling water from the upper reservoirs over time in accordance to the action zones.

Following the severe drought of 2006, the Corps of Engineers revised its operational procedures and developed an Interim Operations Plan for the water storage facilities in the ACF Basin. The main purpose of this Interim Operations Plan (RIOP) is to support the needs of the endangered Gulf sturgeon during the spring spawn and the needs of two species of protected mussels in the summer. The RIOP specifies two parameters applicable to the daily releases from Jim Woodruff Dam: a minimum discharge and a maximum fall rate. The minimum discharges from Jim Woodruff Dam are determined by basin inflow, month, and the basin composite storage. The releases are measured as a daily average flow in cfs at the Chattahoochee gage. The details are presented in Table A.1. The composite storage is calculated by combining the storage of Lake Sidney Lanier, West Point Lake, and Walter F. George Lake. Each of the individual storage reservoirs consists of four Zones. These Zones are determined by the operational guide curve for each project. The basin composite storage utilizes the four Zone concepts as well; i.e., Zone 1 of the composite storage represents the combined storage in Zone 1 for each of the three storage reservoirs. The curves of composite storage zones are shown in Figure A.1.

Georgia Water Resources Institute has developed an alternative reservoir operation policy (GTOP) that meets all the flow requirements for the endangered species required under the RIOP but also keeps the reservoir levels higher during drought periods. Minimum release curves for Woodruff for different seasons under RIOP and GTOP are displayed in Figure A.2. The figure shows that during drought periods when the basin inflow is less than 11,000 cfs RIOP prescribes minimum releases equal to the basin inflow regardless of the future climate outlook. This scenario has the potential of depleting the reservoirs quickly especially during periods of extended droughts since it does not allow for reservoir storage. GTOP, on the other hand, is more flexible in that it makes use of future inflow forecasts and releases less water than RIOP there by avoiding reservoir depletion and enabling quick recovery of reservoir storage especially after prolonged droughts. This flexibility in the GTOP also helps keep reservoir levels higher (higher than 635 ft) in West Point compared to the RIOP routine reservoir draw down (up to 621ft) during winter in preparation for the spring floods.

The second parameter in RIOP is the constraint on the fall rate of the vertical drop at Chattahoochee gage. The fall rates are expressed in units of feet per day (ft/day), and are measured as the difference between the daily average river stage of consecutive calendar days. The maximum fall rate schedule is described in Table A.2.

Table A.1:Minimum Discharge Constraints for Woodruff (RIOP)

Months	Composite Storage Zone	Basin Inflow (BI) (cfs)	Release (cfs)
March -May	Zones 1 and 2	>=34000	>=25000
		>=16000 and <34000	>=16000+50%*(BI-16000)
		>=5000 and <16000	>=BI
		<5000	>=5000
	Zone 3	>=39000	>=25000
		>=11000 and <39000	>=11000+50%(BI-11000)
		>=5000 and <11000	>=BI
		<5000	>=5000
June - November	Zones 1,2, and 3	>=24000	>=16000
		>=8000 and <24000	>=8000+50%(BI-8000)
		>=5000 and <8000	BI
		<5000	>=5000
December-February	Zones 1, 2, and 3	>=5000	>=5000
		<5000	>=5000
All Times	Zone 4		>=5000
All Times	Drought Zone		>=4500

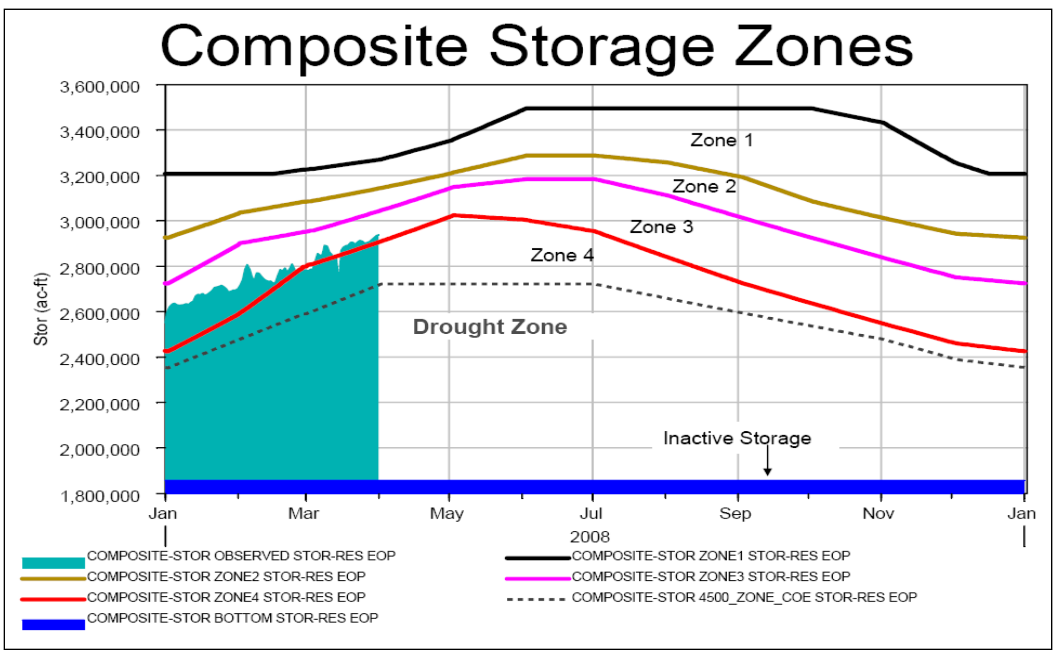


Figure A.1: Composite Reservoir Storage Zone Curves (RIOP)

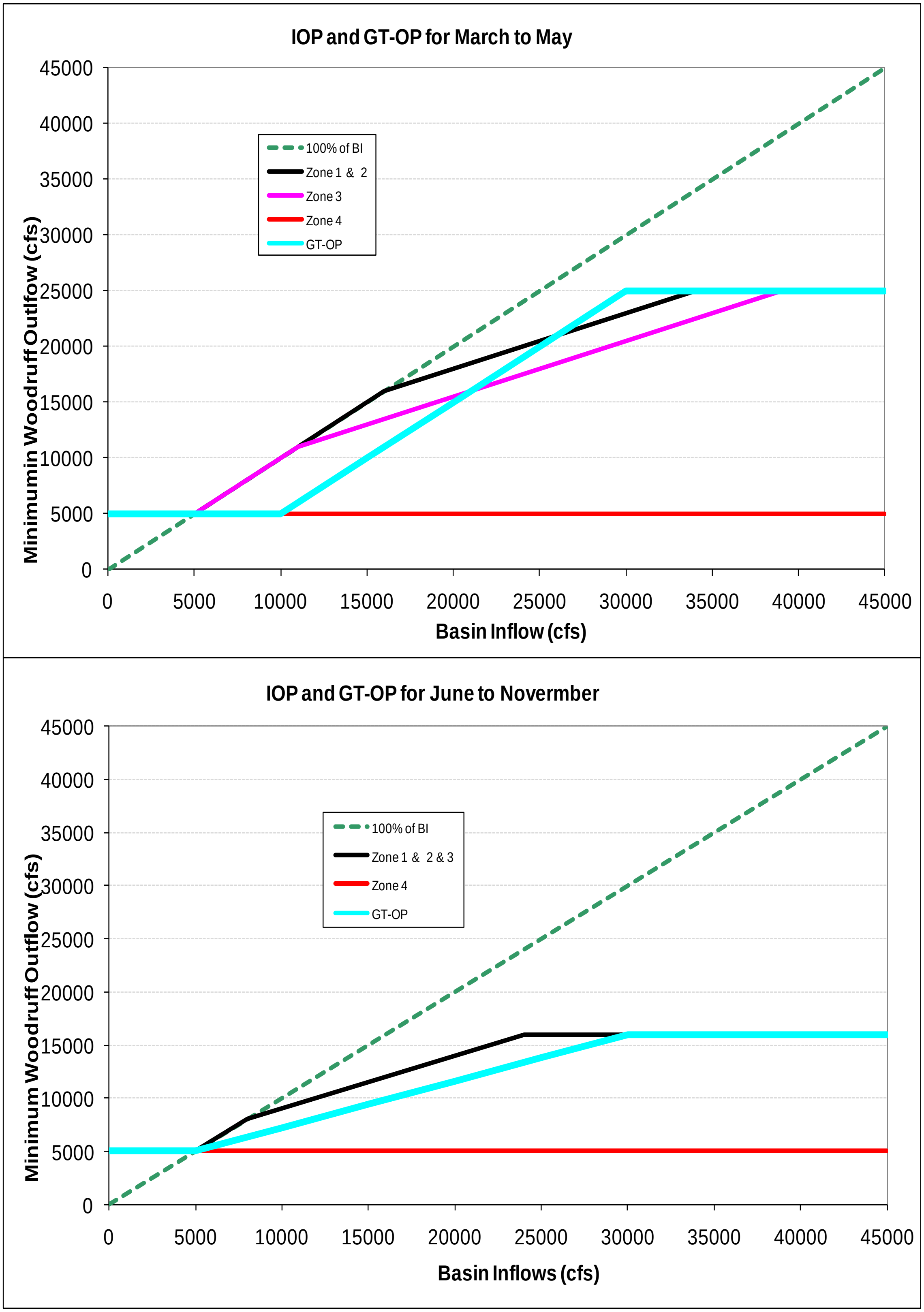


Figure A.2: Minimum Release Requirements at Woodruff (RIOP versus GTOP)

Table A.2: Maximum Fall Rate Constraints at Chattahoochee Gage

Release Range (cfs)	Max. Fall Rate (ft/day) at Chattahoochee Gage
>30000	No Restriction
>20000 and <=30000	1 to 2
>16000 and <=20000	0.5 to 1
>8000 and <16000	0.25 to 0.5
<8000	<=0.25

Note: No restrictions in Composite Zone 4.

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